DIRC-based PID for the EIC Central Detector

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2) Old Dominion University, Norfolk, VA 23529

3) University of South Carolina, Columbia, SC 29208

4) Jefferson Lab, Newport News, VA 23606

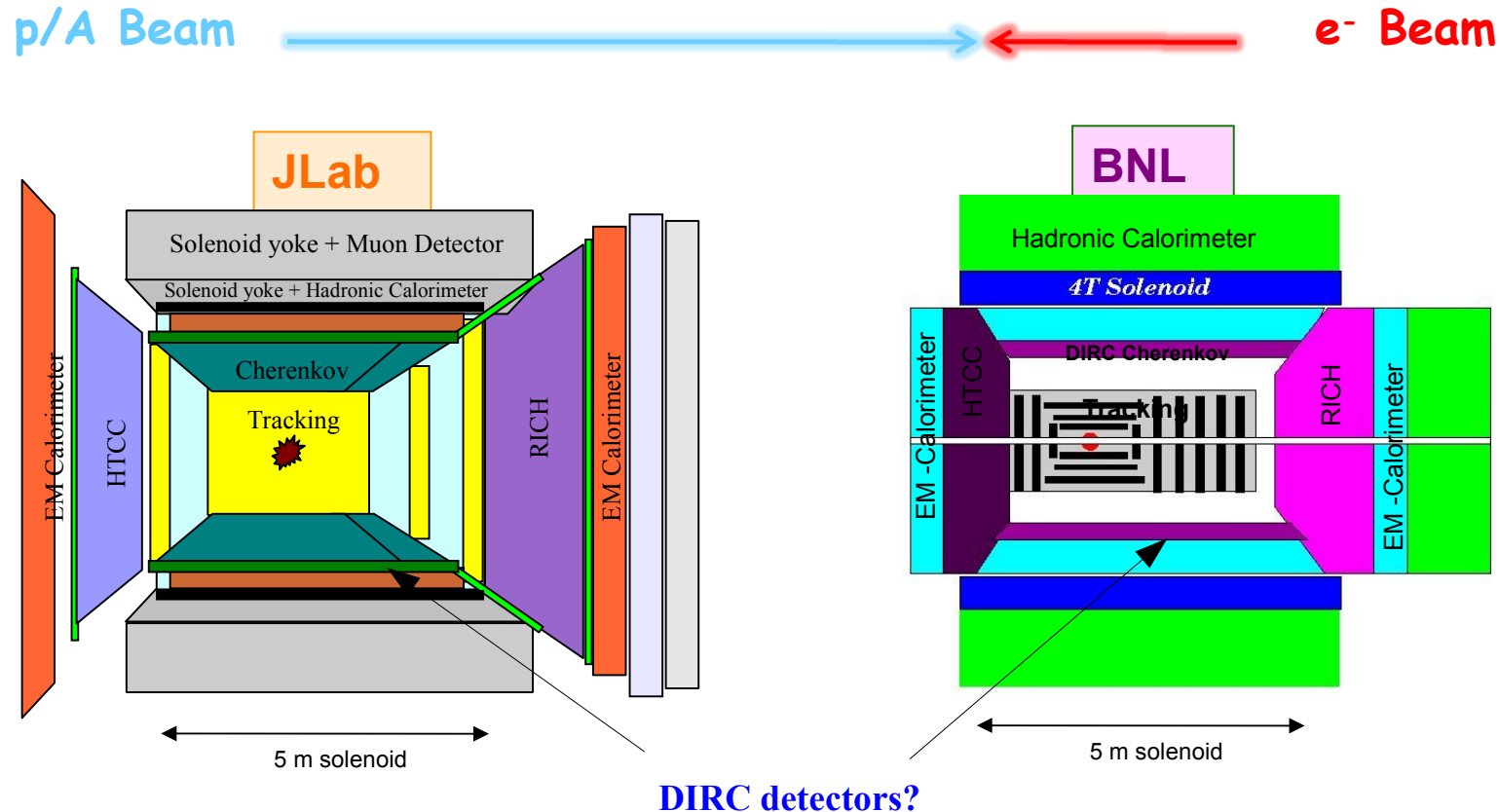5) GSI, 64291 Darmstadt, Germany

BNL, December 12, 2011

Outline

1. PID requirements

2. Proposed R&D

3. Funding Request

EIC central detector cartoons shown at INT-10-3

- Both the JLab and BNL versions of the central detector compatible with a DIRC
  - DIRC requires about 8 cm radial space (2 cm active)

- JLab cartoon also shows a supplementary Cherenkov in addition to the basic DIRC
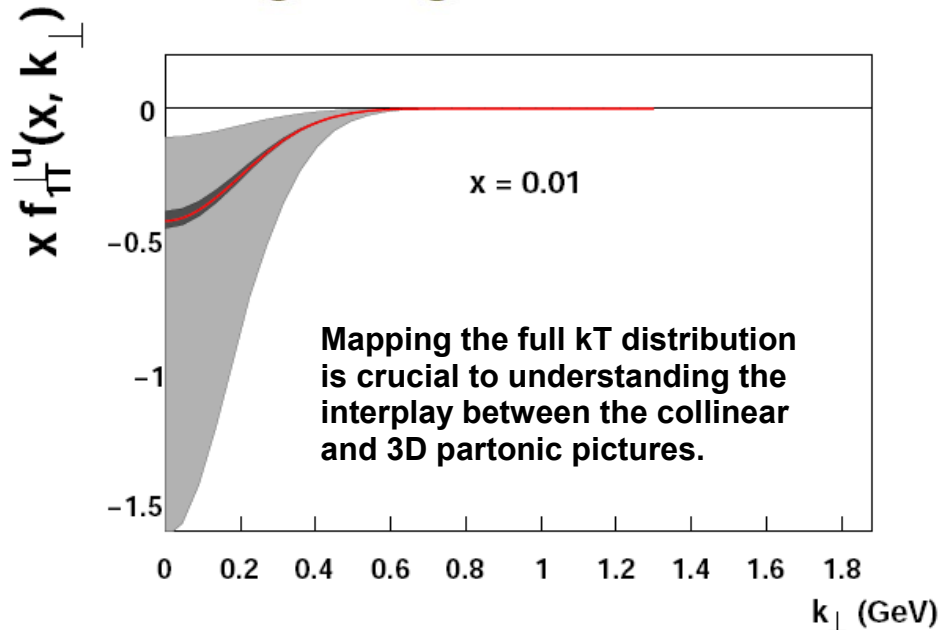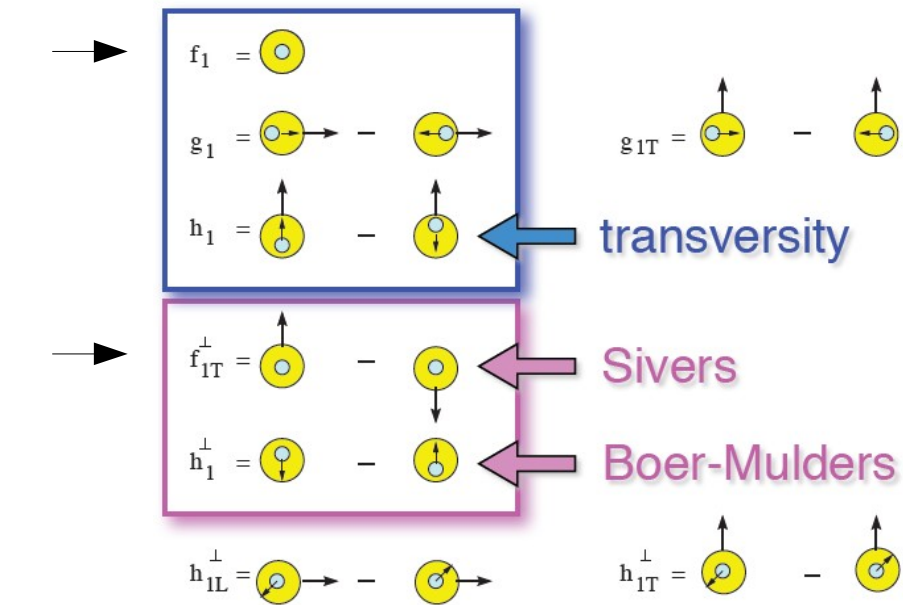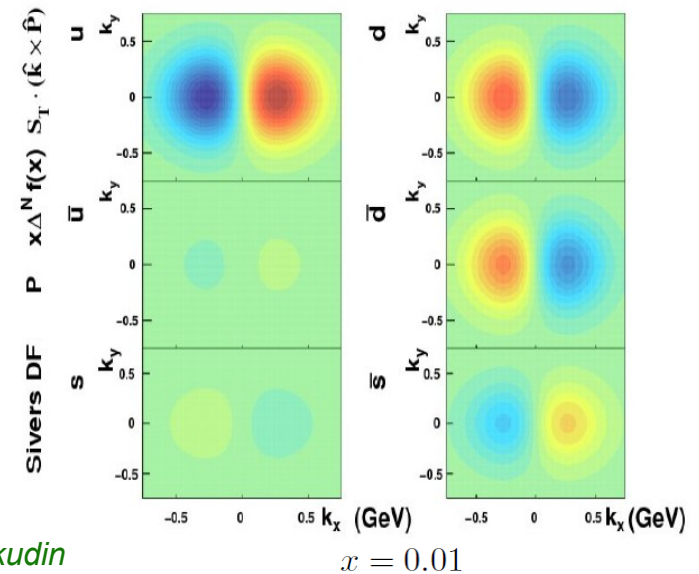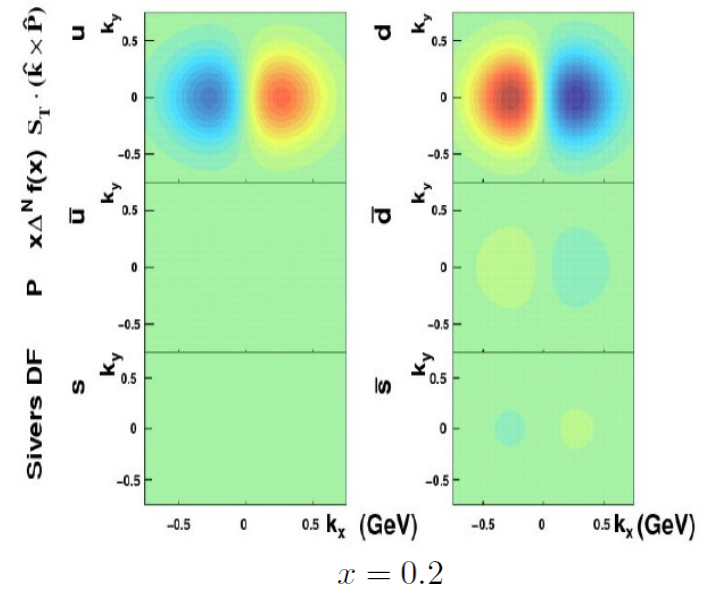
DIS and diffractive mesons

diffractive   **DIS**   No cuts

4 on 250 GeV

4 on 50 GeV

E. Aschenauer et al.

10°

5°
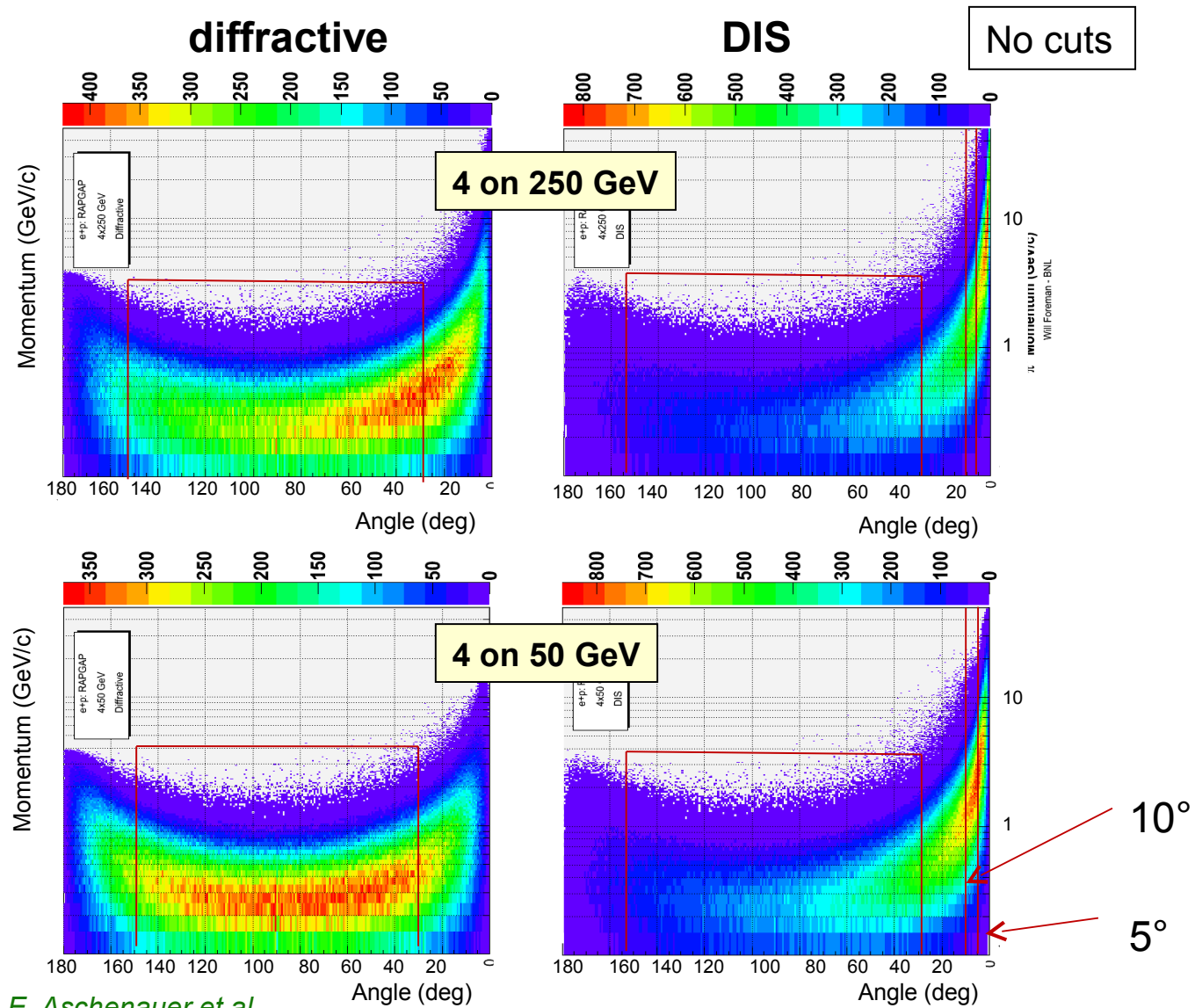
π/K identification up to 4 GeV/c in the central detector seems
sufficient for most DIS and diffractive kinematics, but...

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Transverse Momentum Distributions (TMDs)

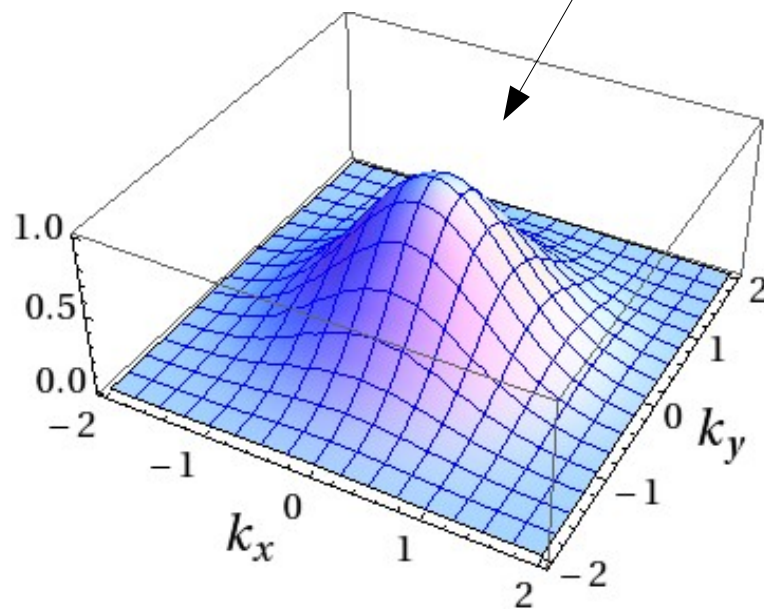

transversity

Sivers

Boer-Mulders

X = 0.01

Mapping the full kT distribution is crucial to understanding the interplay between the collinear and 3D partonic pictures.

A. Prokudin

Sivers functions for u, d and sea
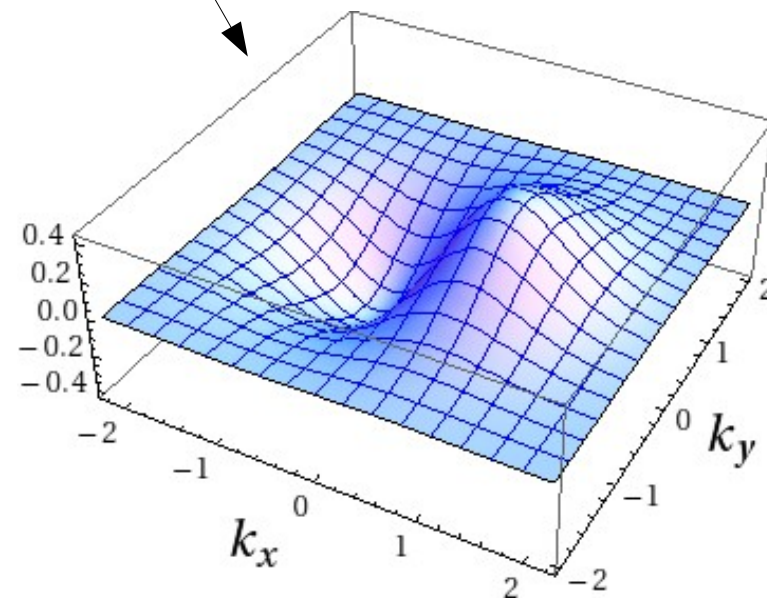
$x = 0.2$

$x = 0.01$

3D distributions with unpolarized target

$$f(x, \mathbf{k_T}, \mathbf{S_T}) = f_1(x, \mathbf{k_T^2}) - f_{1T}^{\perp}(x, \mathbf{k_T^2}) \frac{\epsilon_T^{ij} \mathbf{k_{Ti} S_{Tj}}}{M}$$
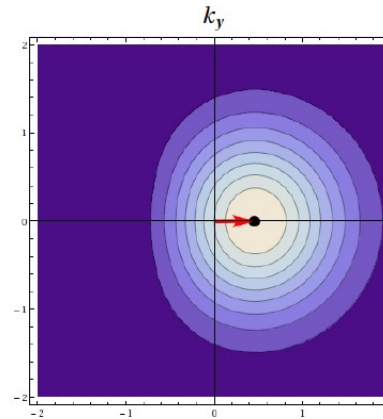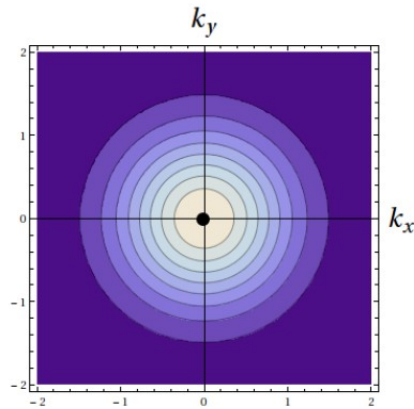
Sivers function

A. Prokudin

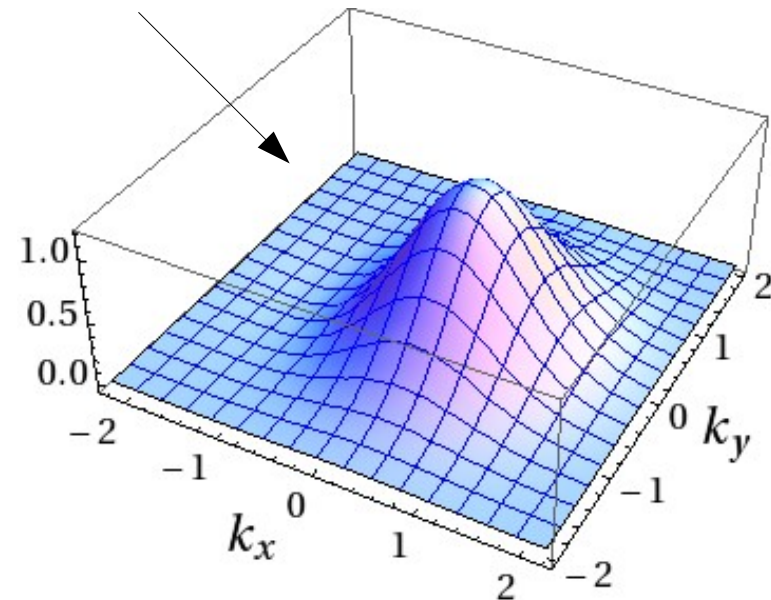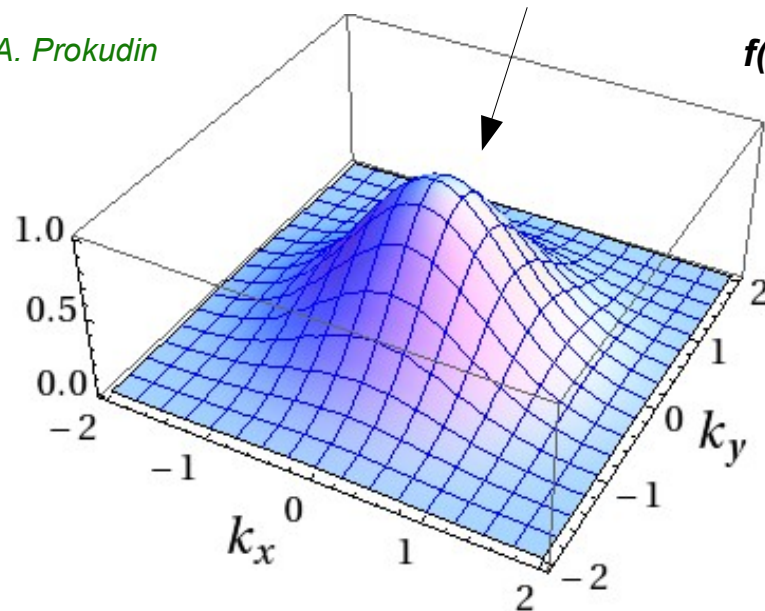# Sivers function and Orbital Angular Momentum

No response to polarization.

Assume spin along y-direction – spin and quark motion are then correlated!

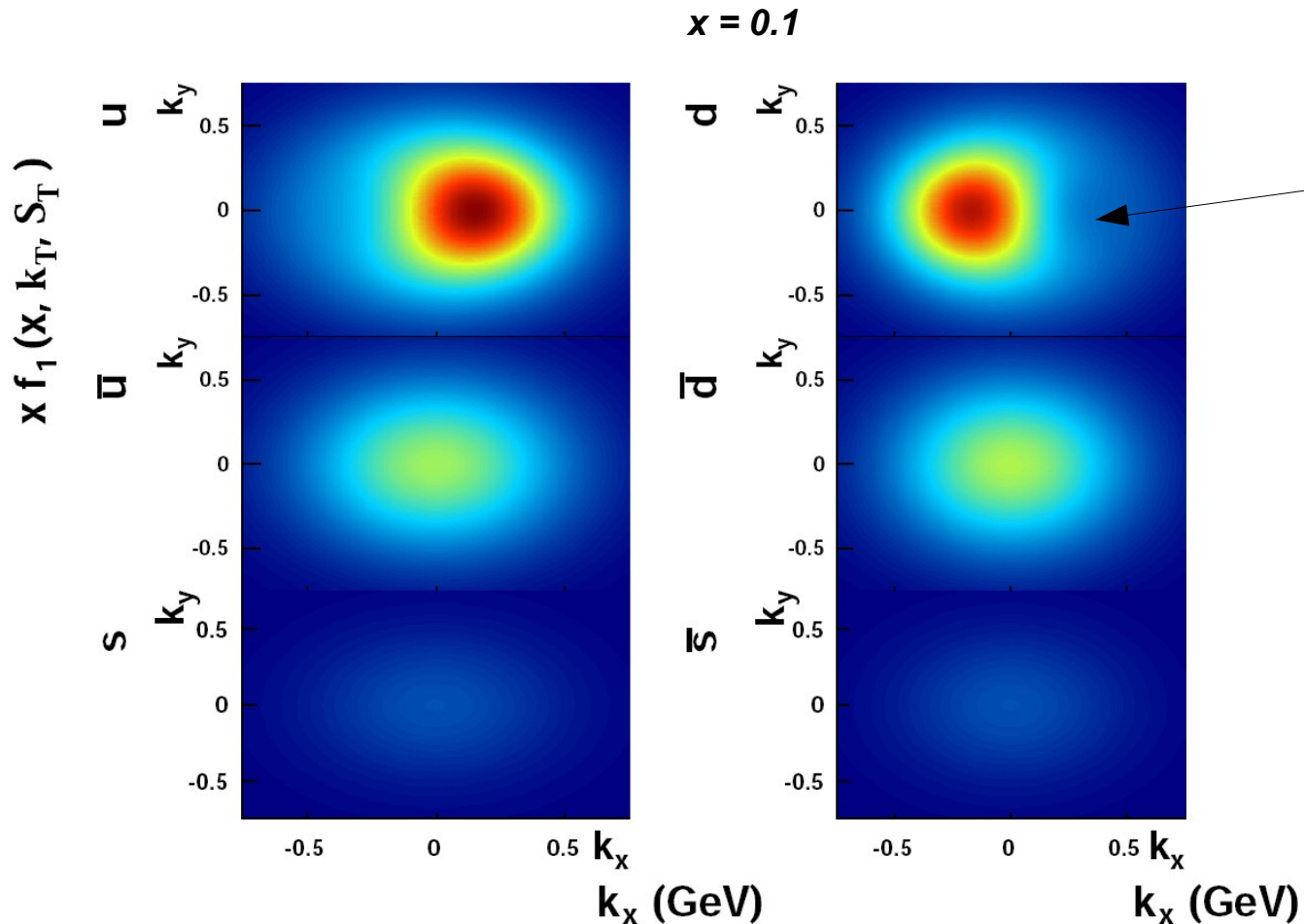*A. Prokudin*

$f(x, k_T, S_T)$

Shift due to Sivers function indicates a non-zero contribution to OAM from quarks.

OAM – a snapshot

x = 0.1

OAM – u and d contribute with opposite signs (c.f. Lattice QCD)

How about anti-quarks?

And strangeness?
Need PID

A. Prokudin

Note: Quantitative extraction of OAM is non-trivial. Theorists still have a lot to do!

Measuring semi-inclusive meson production (SIDIS)

0.2<z<0.8,pi+
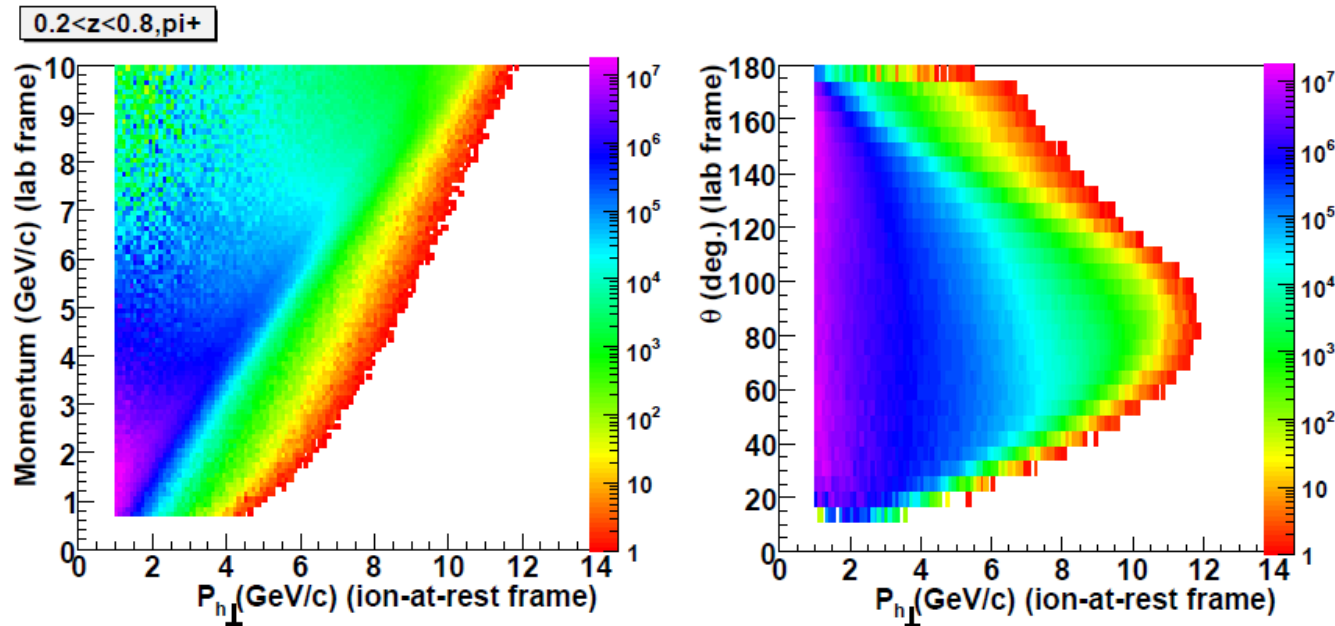
- Momentum of quark: k_T

- Momentum of meson: $p_T \neq k_T$

- p_T defined with respect to photon, not electron

  - Boosted along ion beam direction

  - Thus, generally, $p^{lab} \gg p_T^{rest} > k_T$

- TMDs require detection and identification of mesons (π/K) with lab momenta $\gg$ 1 GeV/c.

- For collinear factorization one needs $p_T \sim Q$.
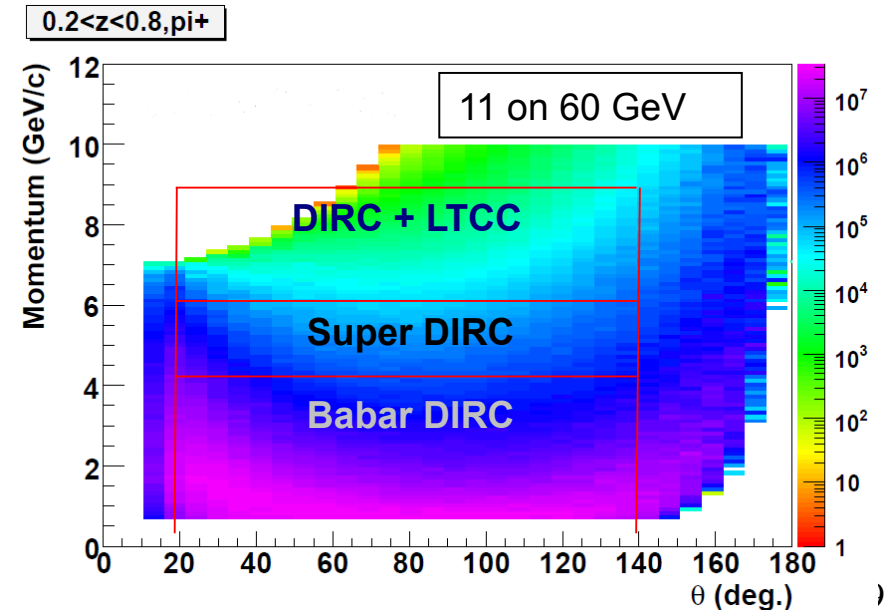
Exclusive meson production *(Q² > 10 GeV²)*
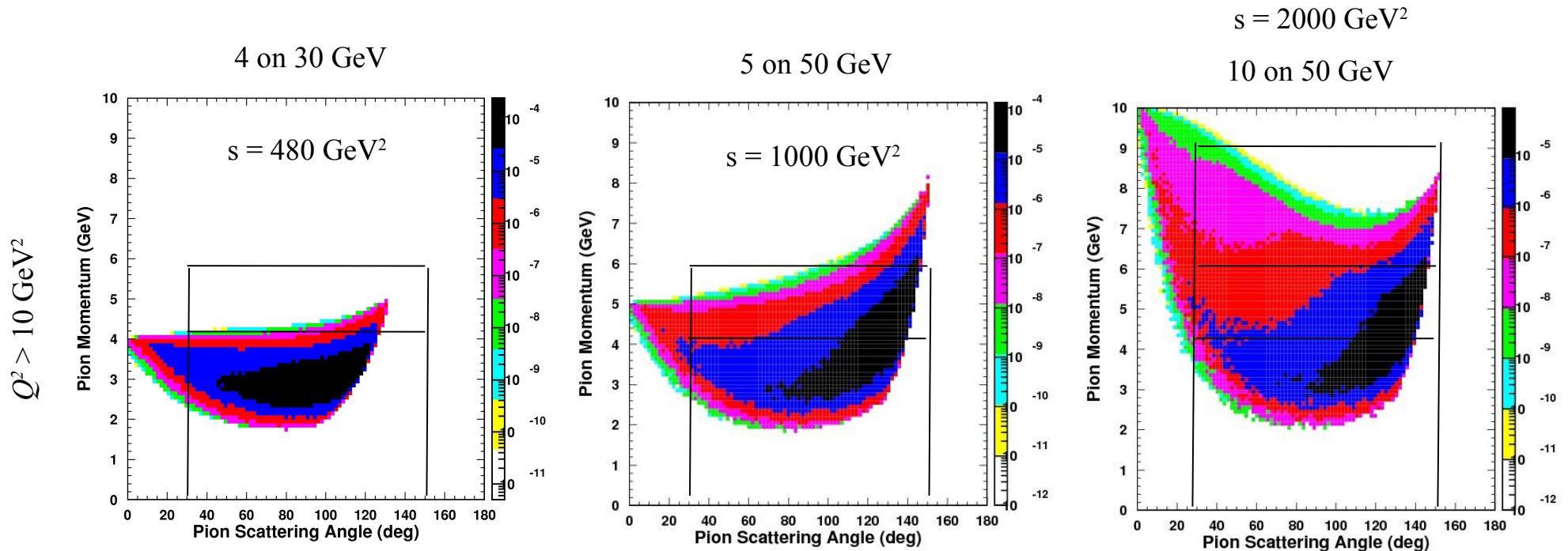
T. Horn

- π/K separation beyond 4 GeV/c (BaBar DIRC) is required already at relatively modest energies.

- Pushing the π/K separation to 6 GeV/c (Super DIRC) would provide almost full coverage for ion energies of 50 GeV, and partial coverage thereafter.

- With π/K separation to 9 GeV/c (DIRC + threshold Cherenkov) reasonable coverage is provided for beam energies up to about 100 GeV.

DIRC principle

- **Charged particle** traversing radiator with refractive index **n** with $\beta = v/c > 1/n$ emits **Cherenkov photons** on cone with half opening angle $\cos \theta_c = 1/\beta n(\lambda)$.

- For $n > \sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.

- **Radiator and light guide**: bar made from Synthetic Fused Silica

- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)

- Photons exit radiator into expansion region, detected on photon detector array. (pinhole imaging/camera obscura or focusing optics)

- DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$ of each photon.
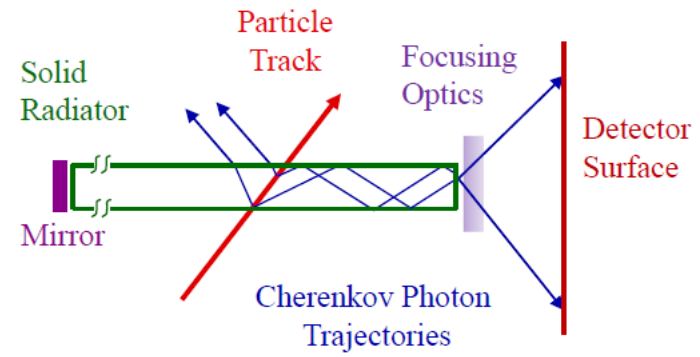
DIRC event reconstruction

Calculate unbiased likelihood for signals to originate
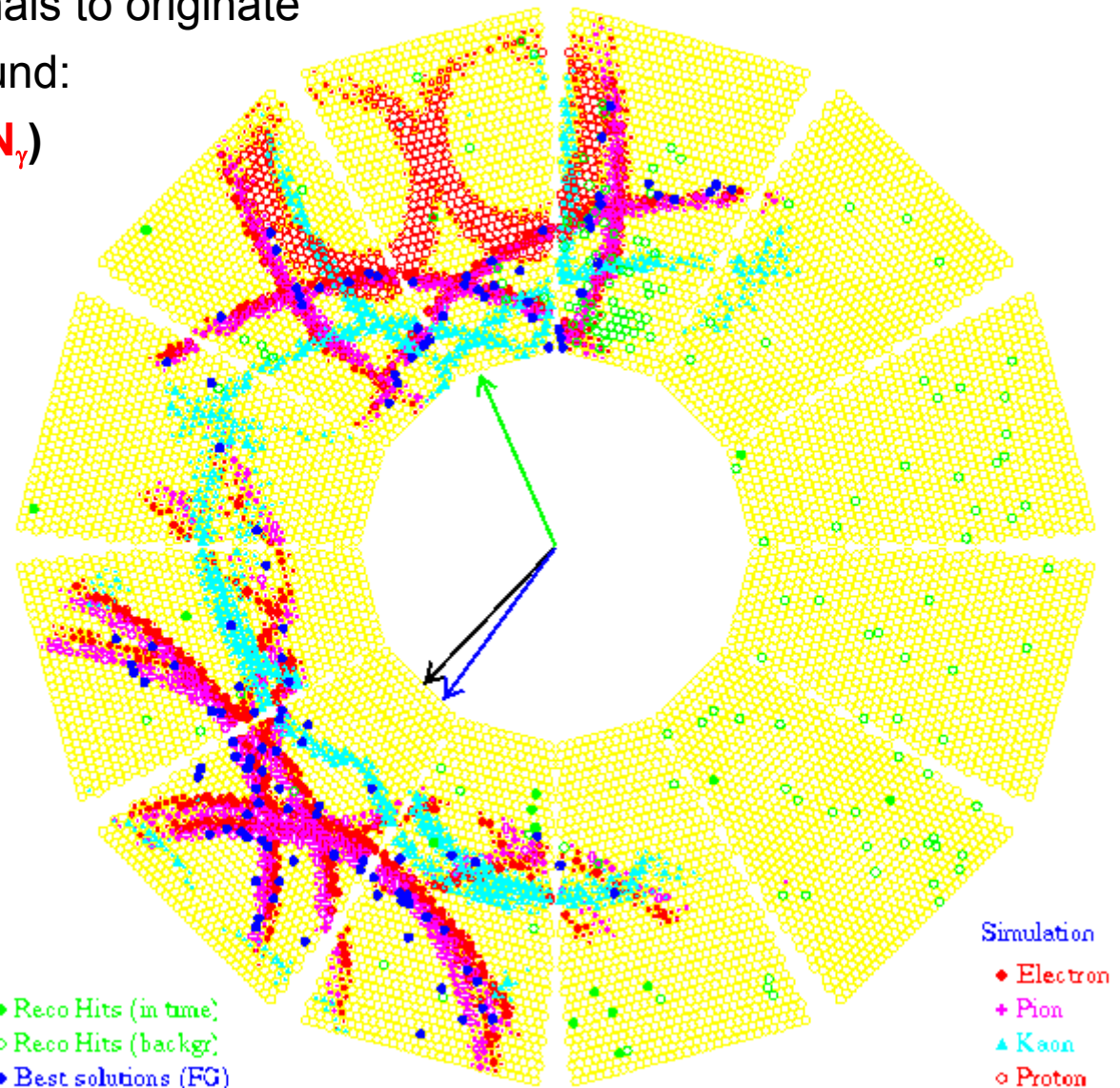from e/μ/π/K/p track or from background:

Likelihood: **Pdf(θ_c) $\otimes$ Pdf(Δt) $\otimes$ Pdf(N_γ)**

Example: comparison of real event to simulated response of BABAR DIRC to e/π/K/p.

Time resolution important for background suppression

± 300 nsec trigger window
(~500-1300 background hits/event)

± 8 nsec Δt window
(1-2 background hits/sector/event)

- Reco Hits (in time)
- Reco Hits (backgr)
- Best solutions (FG)

Simulation
- Electron
- Pion
- Kaon
- Proton
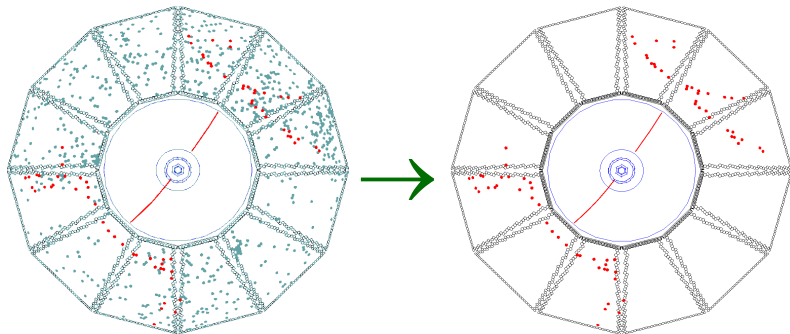
Momentum coverage and Θ_c resolution
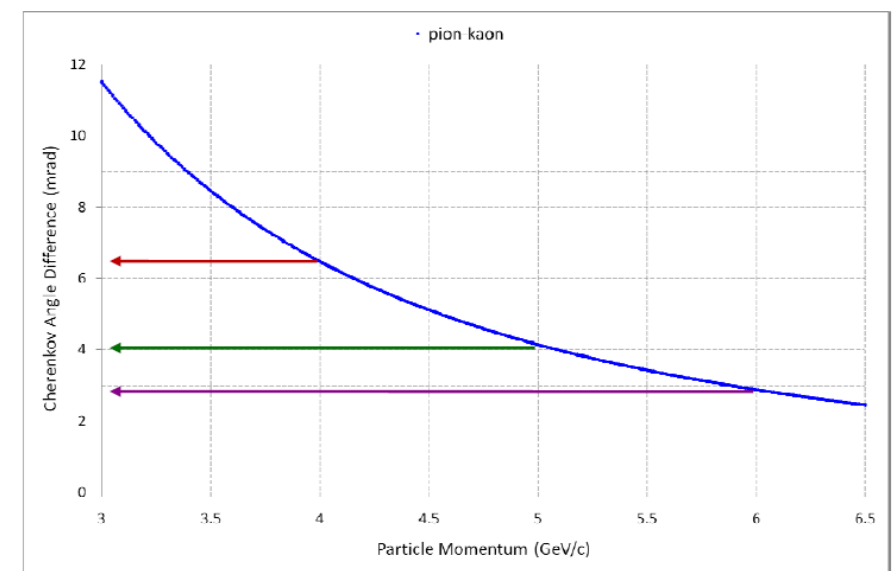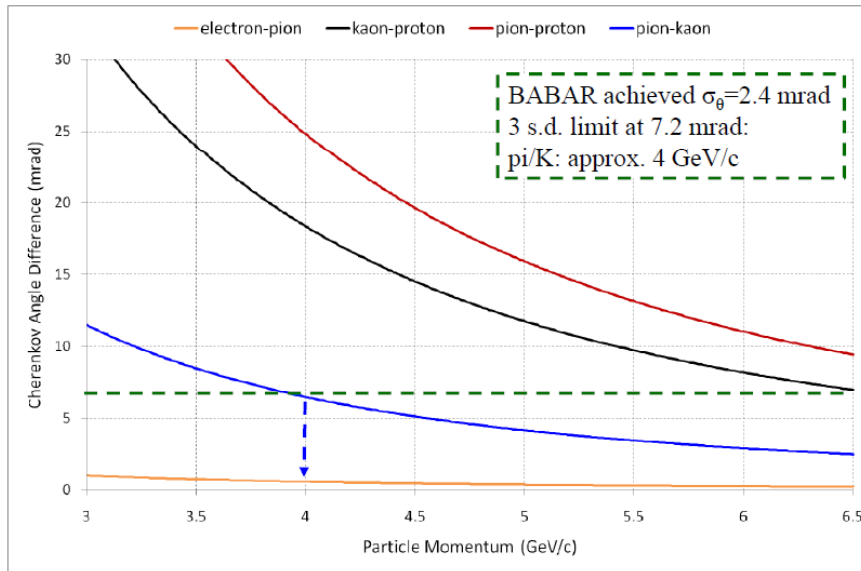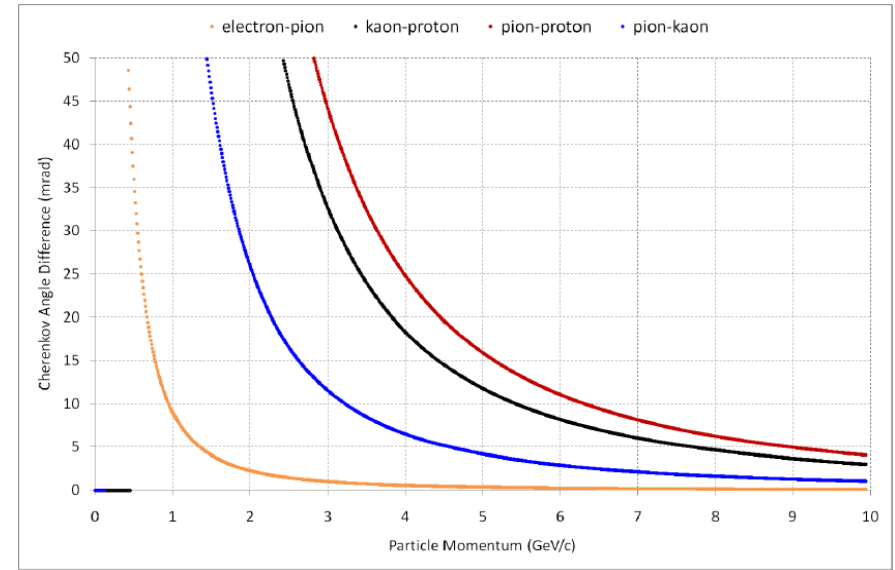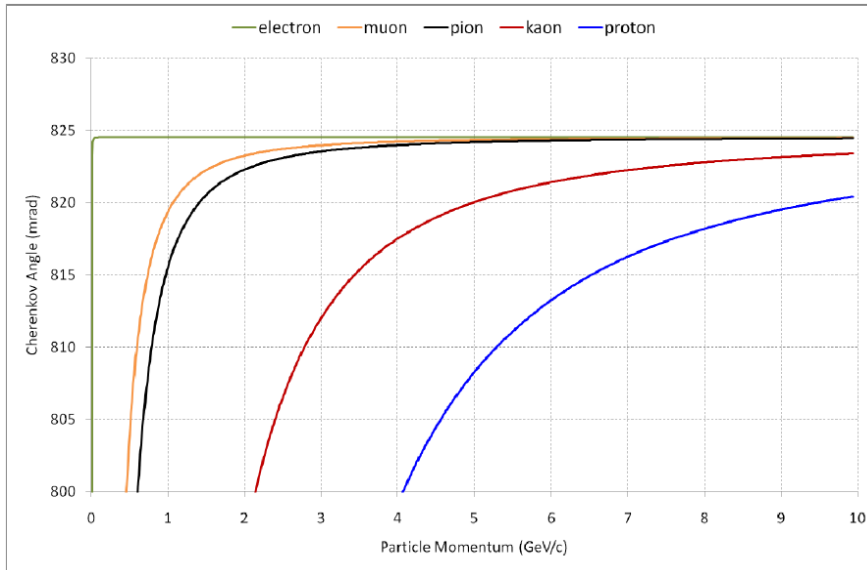
- Extending π/K separation from 4 to 6 GeV/c requires $\sigma_\theta \sim 1$ mrad (vs 2.4 in BaBar – a 58% reduction).

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Improving the Θ_c resolution

$$\sigma_{\theta_c}^{track} = \frac{\sigma_{\theta_c}^{photon}}{\sqrt{N_{p.e.}}} \otimes \sigma^{correlated}$$

Correlated term:
tracking detectors, multiple scattering, etc

$$\sigma_{\theta_c}^{photon} = \sqrt{\sigma_{bar-size}^2 + \sigma_{pixel-size}^2 + \sigma_{chromatic}^2 + \sigma_{bar-imperfection}^2}$$

BABAR-DIRC Cherenkov angle resolution: 9.6 mrad per photon → 2.4 mrad per track

Limited in BABAR by: Could be improved via:

- size of bar image   ~4.1 mrad ----►   - focusing optics ←
- size of PMT pixel   ~5.5 mrad ----►   - smaller pixel size ←   topics for R&D proposal
- chromaticity (n=n(λ)) ~5.4 mrad ----►   - better time resolution ←
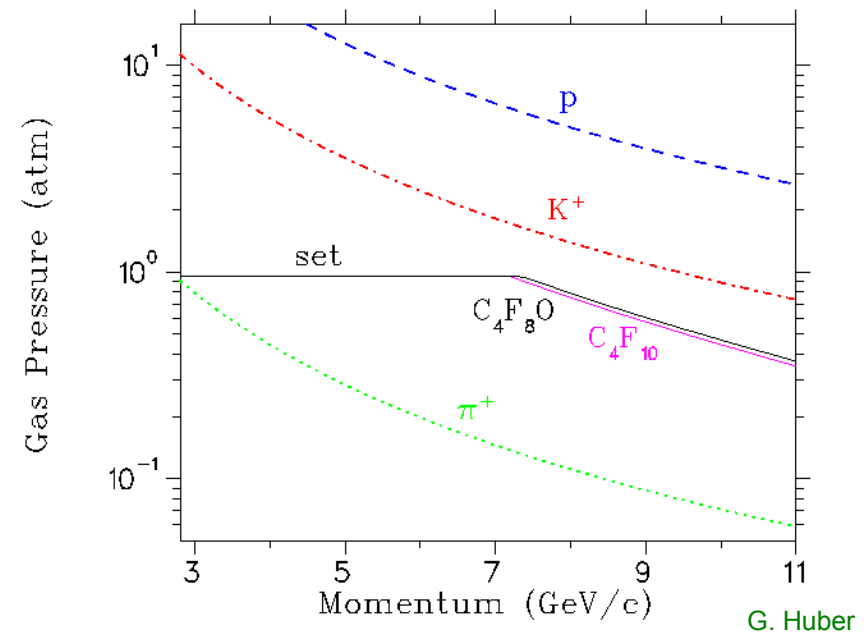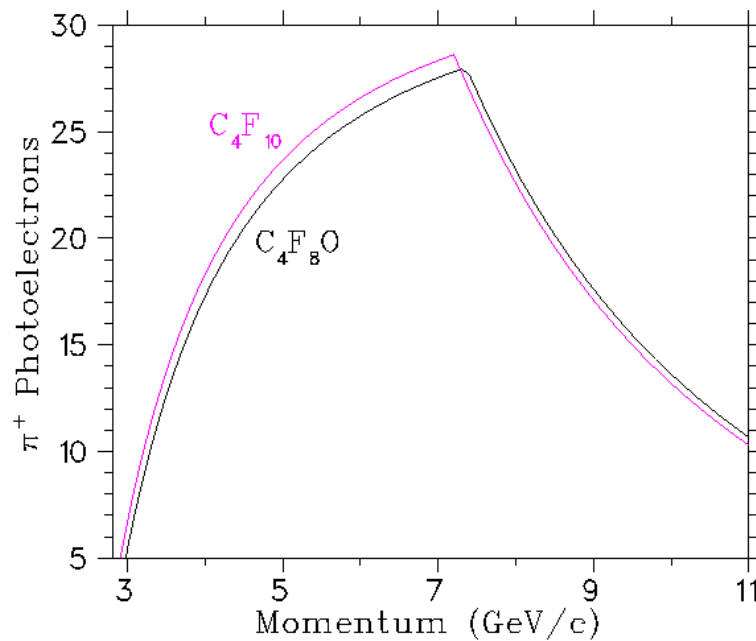
                         9.6 mrad ----►   4-5 mrad (?) per photon

- number of photons   15-50   ----►   - photocathode/SiPM

- DIRC bar thickness can in principle also be increased beyond the 17 mm (19% r.l.) used in Babar
- Excellent 3D imaging (2 spatial + time) essential for pushing performance beyond state-of-the-art

Supplementary threshold Cherenkov detector

Number of p.e. in 60 cm of gas (left), and threshold as function of gas pressure (right)

- If needed, a supplementary threshold Cherenkov can provide
  - e/π separation for 1-3 GeV/c
  - π/K separatation for 4-9 GeV/c (higher with some underpressure)

- A radiator thickness of 60 cm (+ 10 cm for readout ?) is clearly adequate, 40 cm may be sufficient

- C_4F_{10} gas can be replaced by the more eco friendly C_4F_8O

R&D goals

1. Demonstrate feasibility of using a DIRC in hermetic EIC detector

- Compact readout "camera" (expansion volume + sensors)
- Operation in high magnetic fields (up to 2-4 T)

2. Investigate possibility of pushing state-of-the-art performance

- Extend 3σ π/K separation beyond 4 GeV/c, maybe as high as 6 GeV/c
    - also improve e/π and K/p separation

3. Study integration of the DIRC with other detector systems

- Supplementary gas Cherenkov?
- Integration with solenoid, tracking, calorimeter, etc
- Accelerator backgrounds (in collaboration with SLAC)

DIRC simulations and EV design

- Ray-tracing software will be used for parameter studies and the initial design of the EV

- DRCPROP, written by C. Schwarz has been transferred to JLab

- Detailed studies of the EV design will be performed using GEANT4

- This can then be implemented into the GEANT4 (GEMC) framework used for the EIC detector
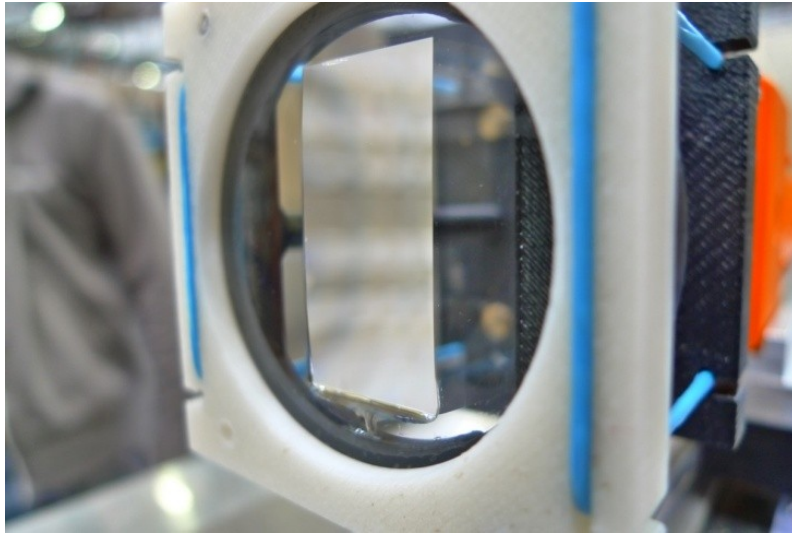 - Integration studies

H. Seraydaryan
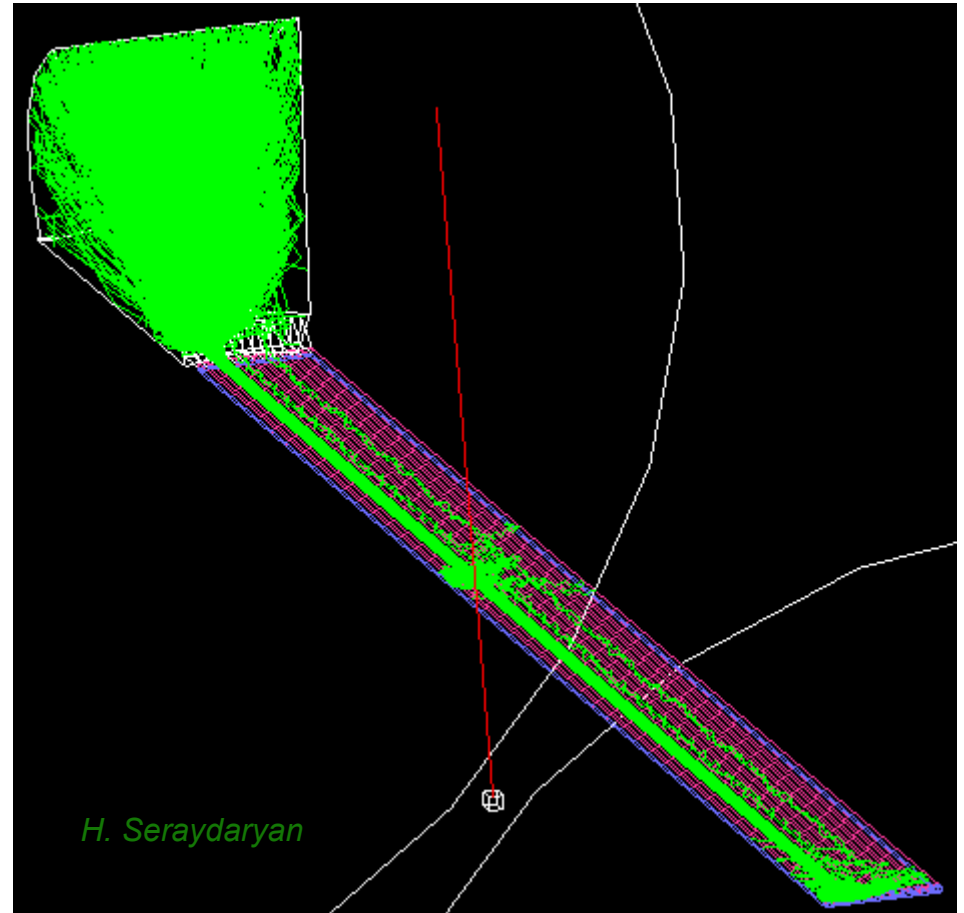
First tests of implementing a DIRC into GEANT4 at ODU/JLab using the BaBar geometry

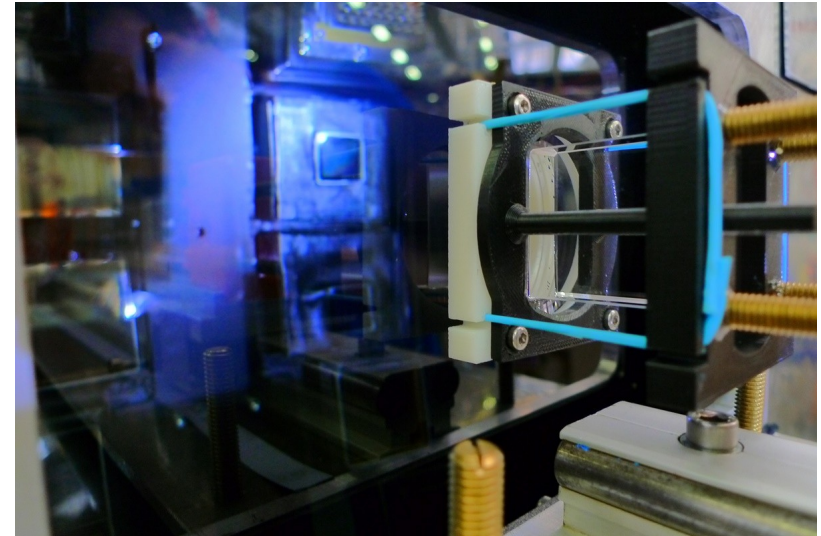# PANDA: successful in-beam tests at GSI in 2009
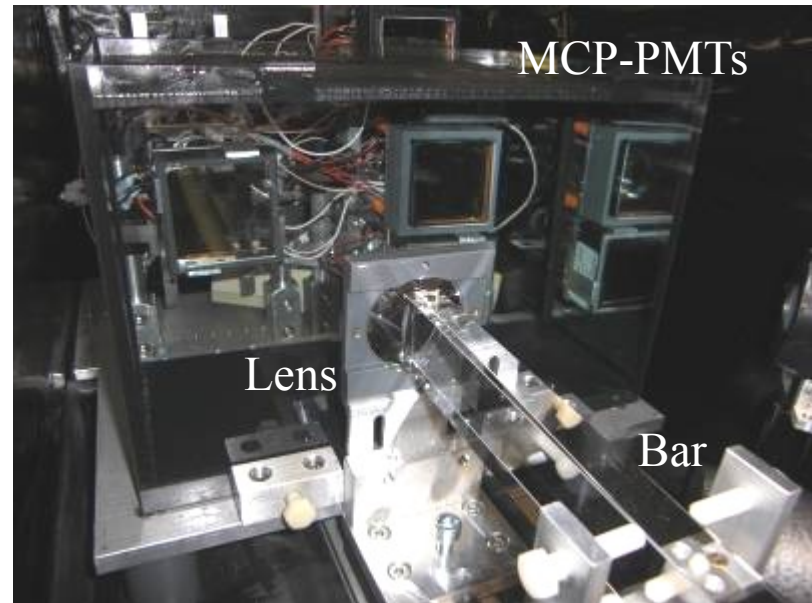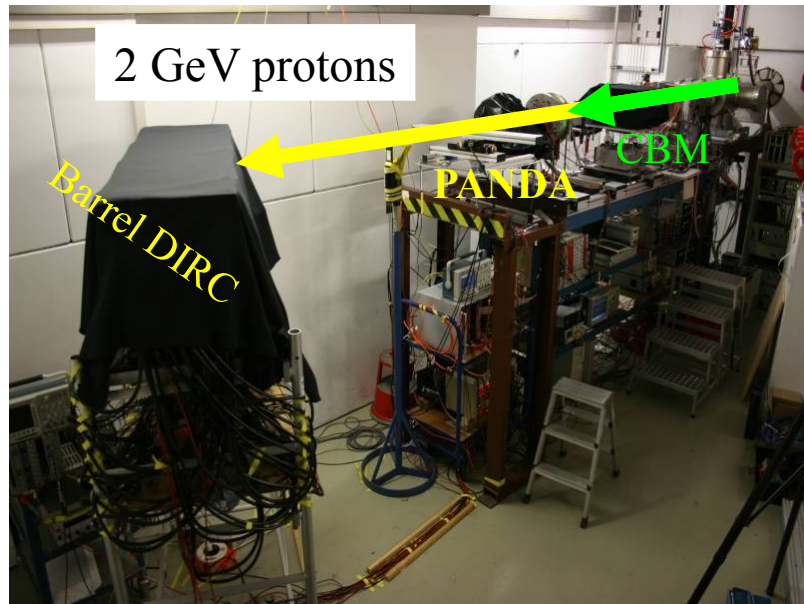
- First expansion volume (EV) prototype

PANDA: EV prototype during 2011 tests at CERN

Simple plano-convex focusing lens attached to bar
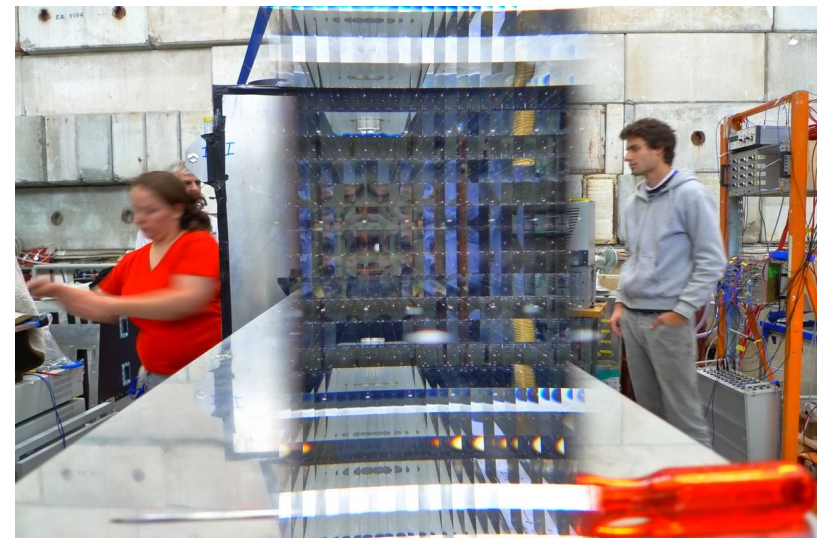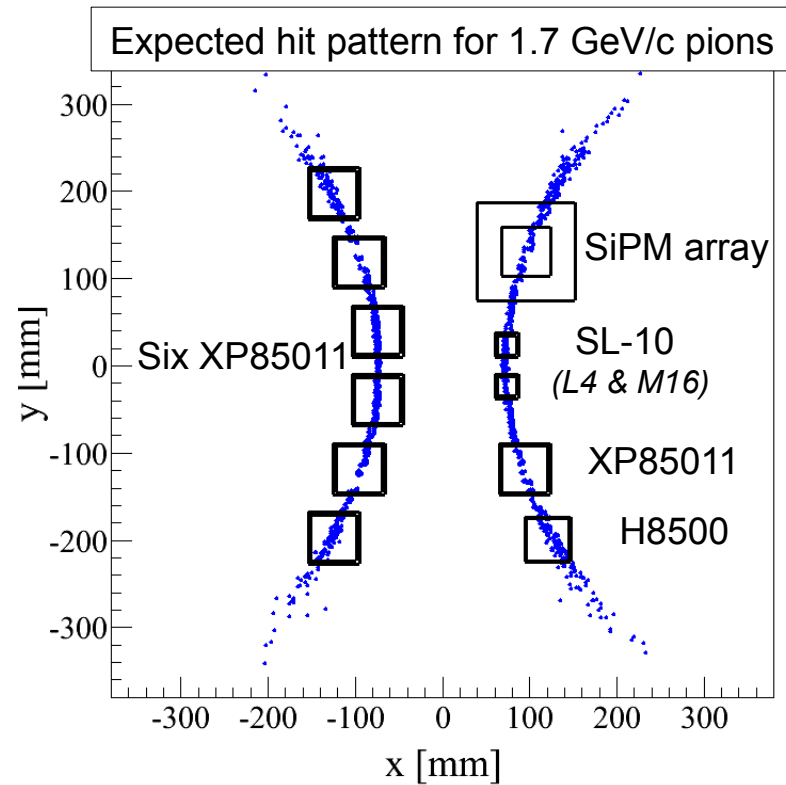

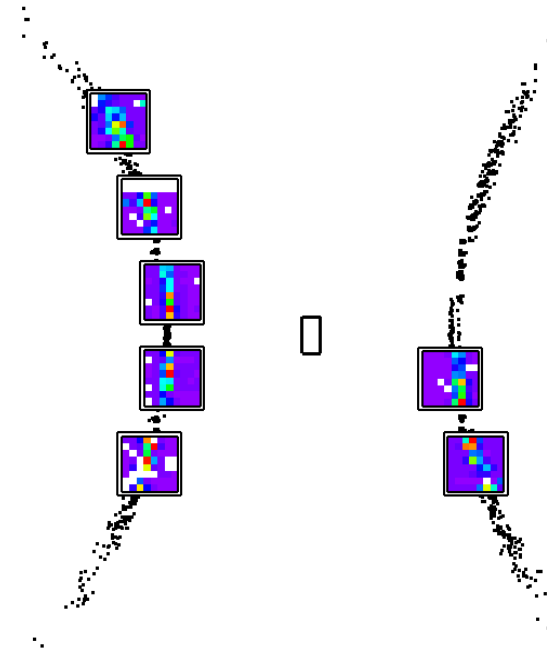**Looking into mineral-oil filled EV; MCPs in back**

- Full-scale expansion volume
  - EV: 800 x 800 x 300 mm
  - Bar: 17 x 35 x 1225 mm

- Focusing lens attached to end of bar
  - Different AR coatings

PANDA: results from 2011 tests at CERN

Expected hit pattern for 1.7 GeV/c pions

SiPM array

Six XP85011

SL-10
(L4 & M16)

XP85011

H8500

Simulation

Data

PANDA: EV prototype readout electronics
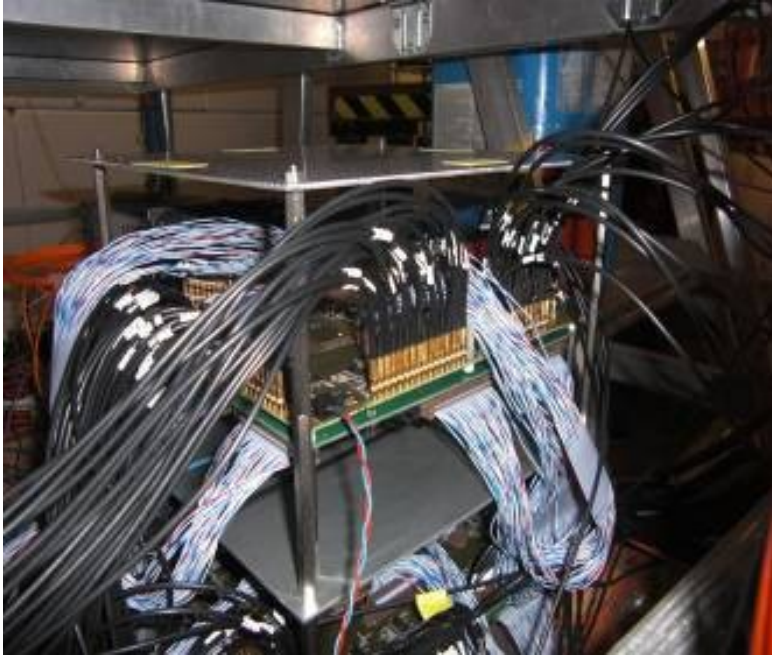
HADES TRB readout system
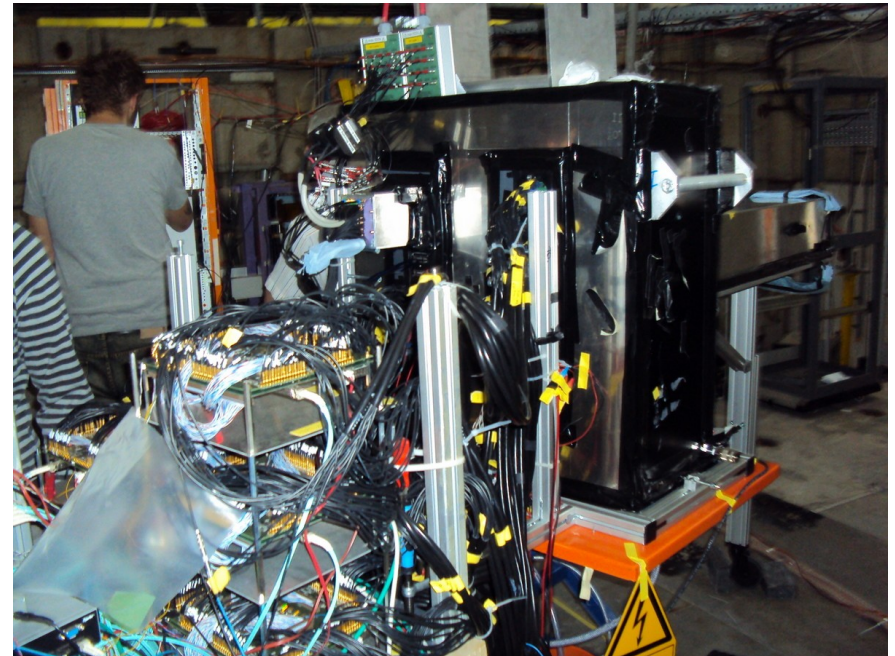
EV prototype with readout at CERN

- PANDA prototype at CERN: 640 channel HADES TRBv2 with TOF-addON

- EIC tests / prototype could use new HADES TRBv3 (expected in spring of 2012)
  - TRBv2 with TOF-addON: 128 channels with fast TDC (~100 ps/count)
  - TRBv3 will have ~10 ps/count and more channels per board (but similar price per channel)

- Good timing important for improving chromatic effects in long bars

PANDA: new fused silica EV prototype
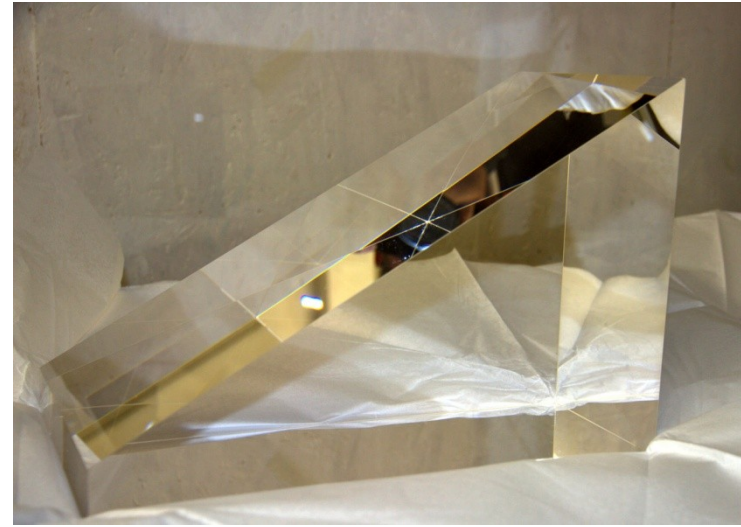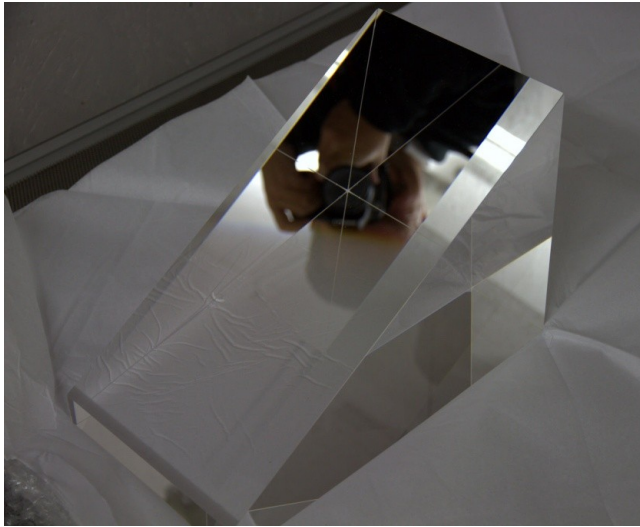
Prism for new PANDA fused-silica expansion volume prototype (size: 170 x 300 x 200 mm @ 30º)

- *Recent development:* the next-generation PANDA DIRC expansion volume prototype will be smaller and may use fused silica instead of mineral oil.

- **This technology is the ideal starting point for the EIC DIRC R&D effort!**
  - **The EIC project will have an independent test / prototype setup at GSI**
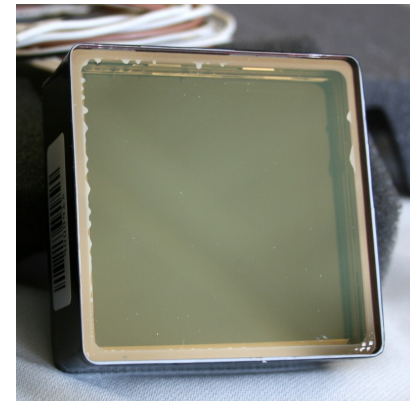
New Photonis XP85012/A1 MCP-PMT; Size: 59 x 59 x 14 mm, 8x8 anode pads

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High B-field sensor tests - magnet

LHe
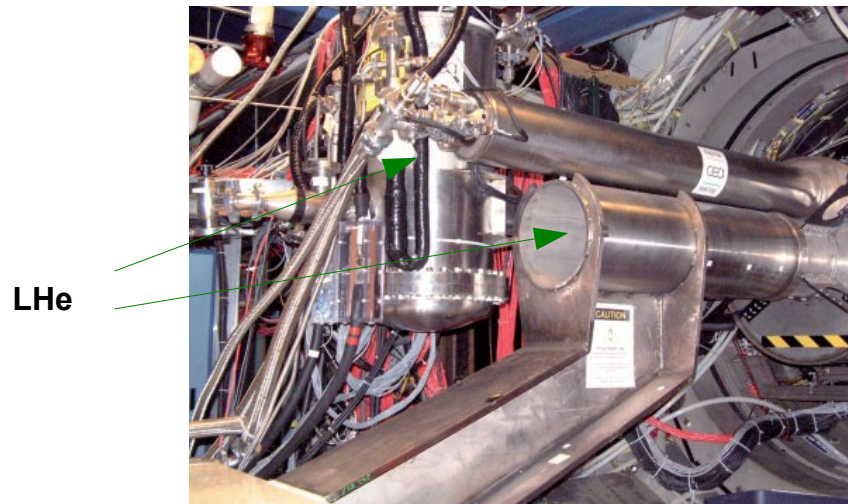
DVCS solenoid in CLAS (Hall B)

Solenoid in pre-delivery test setup

DS Flange

Main coil

Compensation coil

- Superconducting 4.7 T solenoid
    - 250 mm bore
    - Compensation coils reduce external field
    - Used for DVCS at 6 GeV: well understood field

- Permanent setup in new Test Lab
    - LHe supply from central He liquifier

High B-field sensor tests - box

Sensor Test Box – Side (Back) View
(Side Fittings not shown)

(Wood) Lid with inner sleeve for Light tight fit

Outer Surfaces of Lid painted Black

Wooden box

Inner Surfaces painted diffuse White

6"

Optical breadboard

Aluminum Rail Mount

6"

Sensor on optomechanical mount

Sensor Test Box – Top View

Fiber Optic input from LED

Optical Diffuser

Optical breadboard

Sensor sample

6"

Fittings for power or data lines

8"

Optomechanics for rotation and translation

- Non-magnetic, light-tight, temperature-controlled test box designed by C. Zorn

- Large enough for test of SiPMs (G-APDs), MCP-PMTs, and other sensors

- Modular design will allow different boxes to be inserted into solenoid.

Detector integration: DIRC and gas Cherenkov
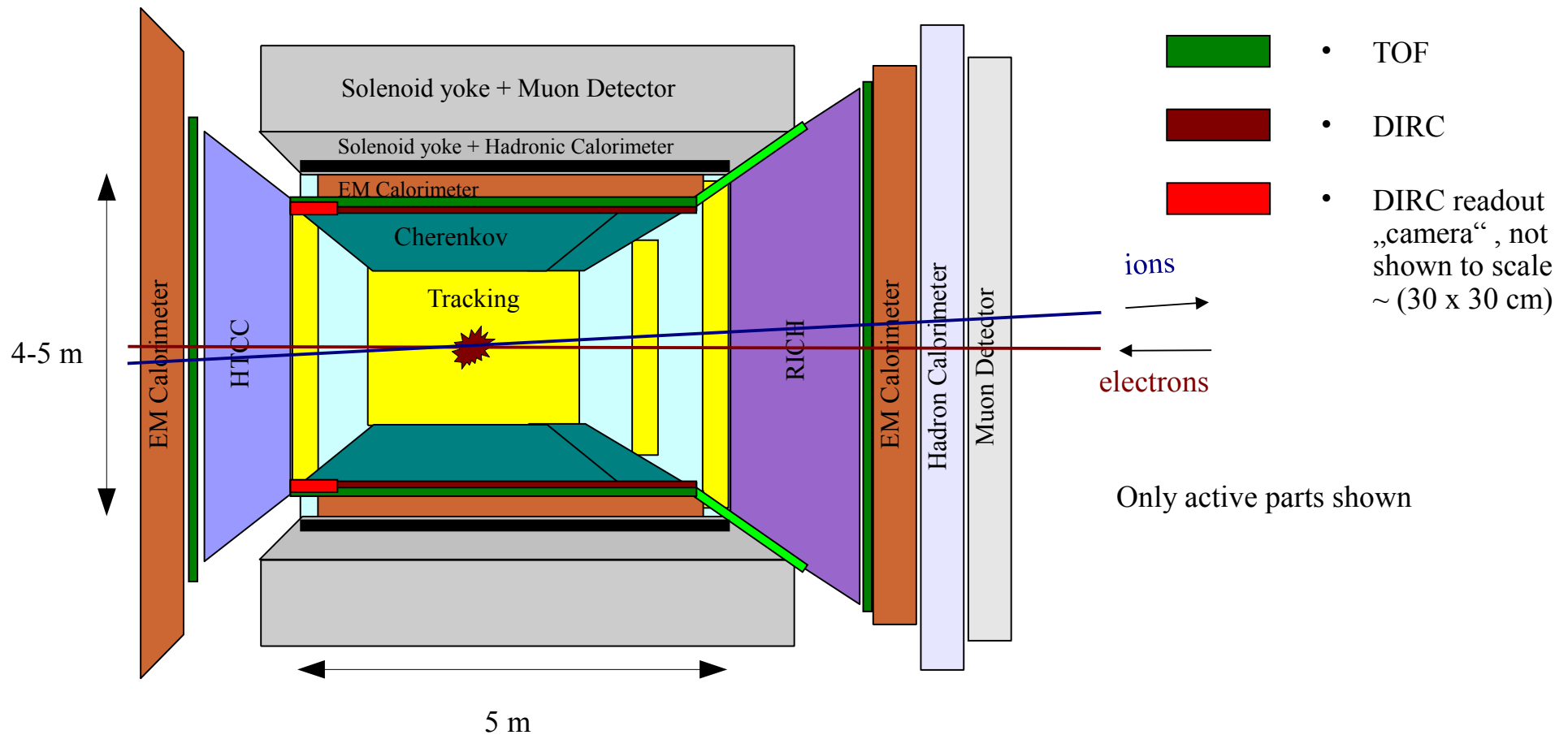
- Impact of DIRC on other detector components

- Placement of DIRC with respect to gas Cherenkov (inside / outside)

- Impact on endcap if DIRC bars are extended through iron.

Detector integration: Super-DIRC
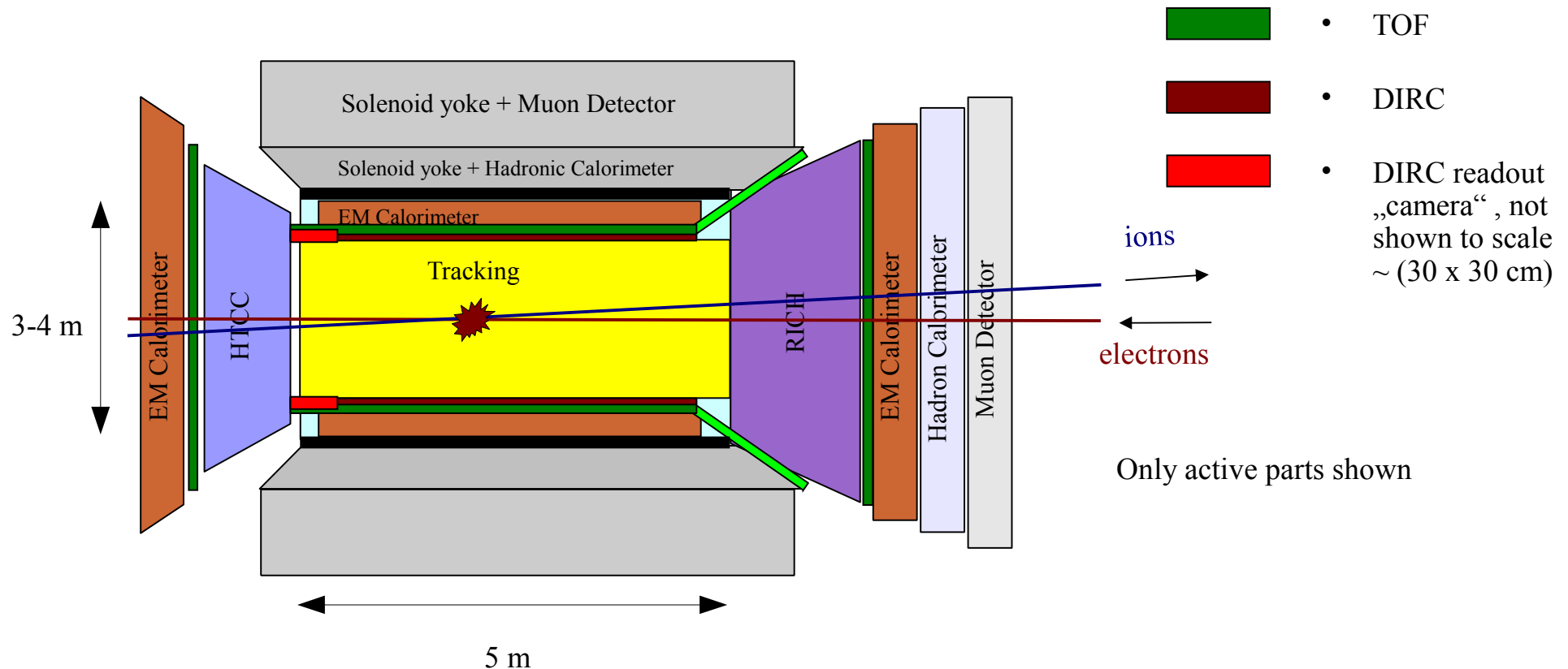
- Compact PID can provide more space for tracking or make the detector radius smaller, making it easier to support higher B-field.

- Need to understand how optimizations of solenoid and tracking will impact size of DIRC.

Primary responsibilities

1. Simulations of DIRC performance and design of EV prototype

- Old Dominon University

2. Integration with the EIC detector

- Catholic University of America

3. Prototyping and hardware test (except high magnetic fields)

- GSI (Helmholtzzentrum für Schwerionenforschung)

4. Sensor test in high magnetic fields

- University of South Carolina and Jefferson Lab

Note: **The proposal is a collaborative effort and most institutions will contribute to more than one of the areas above regardless of their primary responsibility**

Funding Request for FY12 (and FY13)

Budget	FY11	FY12	FY13	Total
Postdoc (50%)	$53,290	$54,000	$55,000	$162,290
Students	$8,300	$13,764	$13,764	$35,828
Hardware	$41,970	$58,630	$57,200	$157,800
Travel	$11,440	$13,606	$14,036	$39,082
Total	$115,000	$140,000	$140,000	$395,000

The salaries for the postdoc and students include university overhead. Matching funds are available for the postdoc. The travel includes JLab or USC overhead. Hardware includes JLab or CUA overhead.

Budget	FY11	FY12	FY13	Total
Old Dominon Univesity (ODU)	$53,290	$54,000	$55,000	$162,290
Catholic University of America (CUA)	$9,800	$8,300	$8,300	$26,400
University of South Carolina (USC)		$7,606	$7,606	$15,212
JLab and GSI (through MoU)	$51,910	$70,094	$69,094	$191,098
Total	$115,000	$140,000	$140,000	$140,000

Summary

1. A DIRC offers interesting capabilities for the EIC detector

- Standalone: more space for tracking, cost reduction (magnet, endcaps, calorimeter)
- With supplementary gas Cherenkov: high p_T-coverage

2. We propose a 3-year R&D effort

- Feasibility studies (simulations, component tests)
- Integration with EIC detector (simulations)
- Extending performance beyond state-of-the-art (simulations, prototyping)
- New facility for sensor test in high magnetic fields
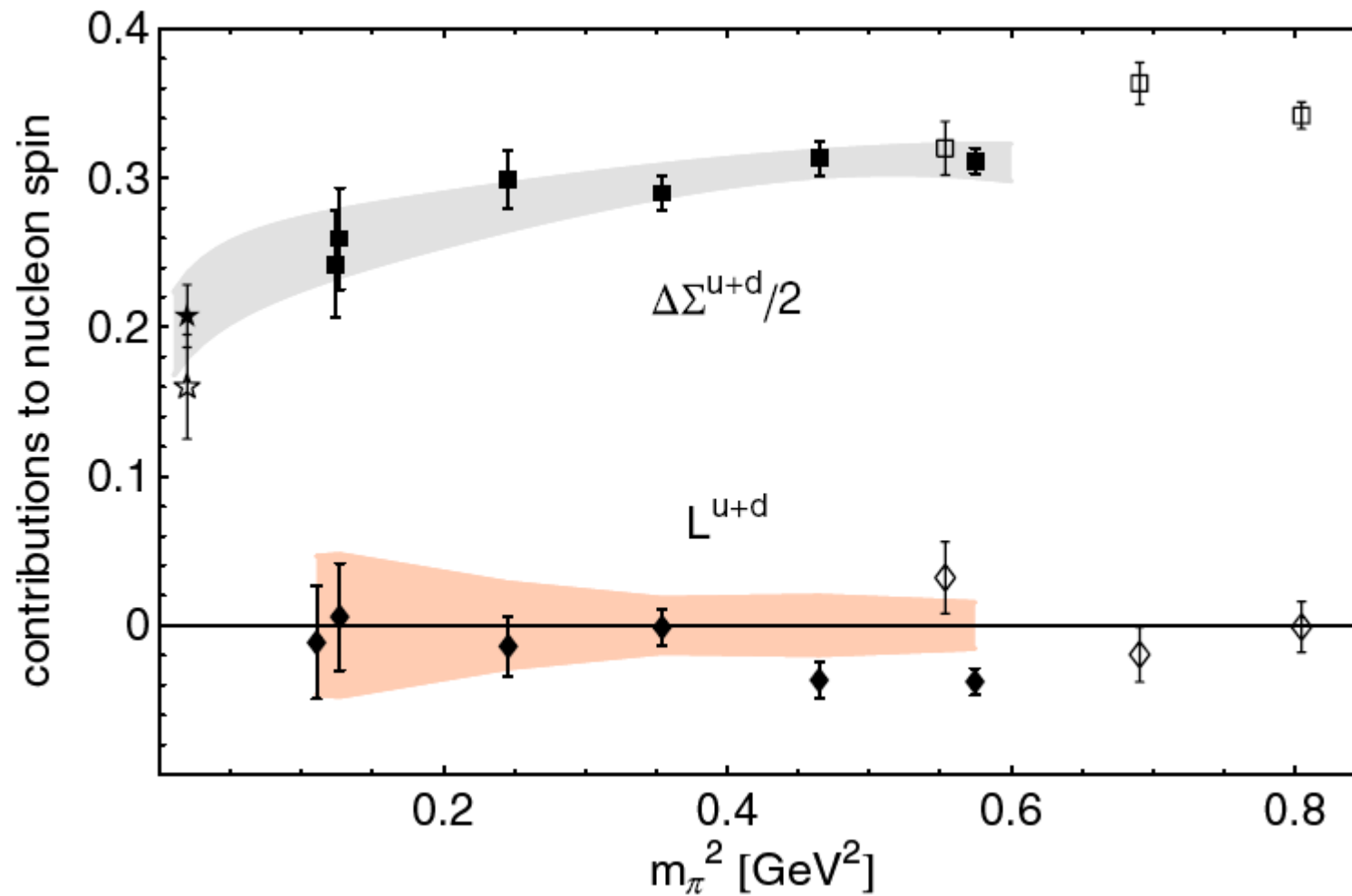
3. FY11 effort is well underway!

Thank you!

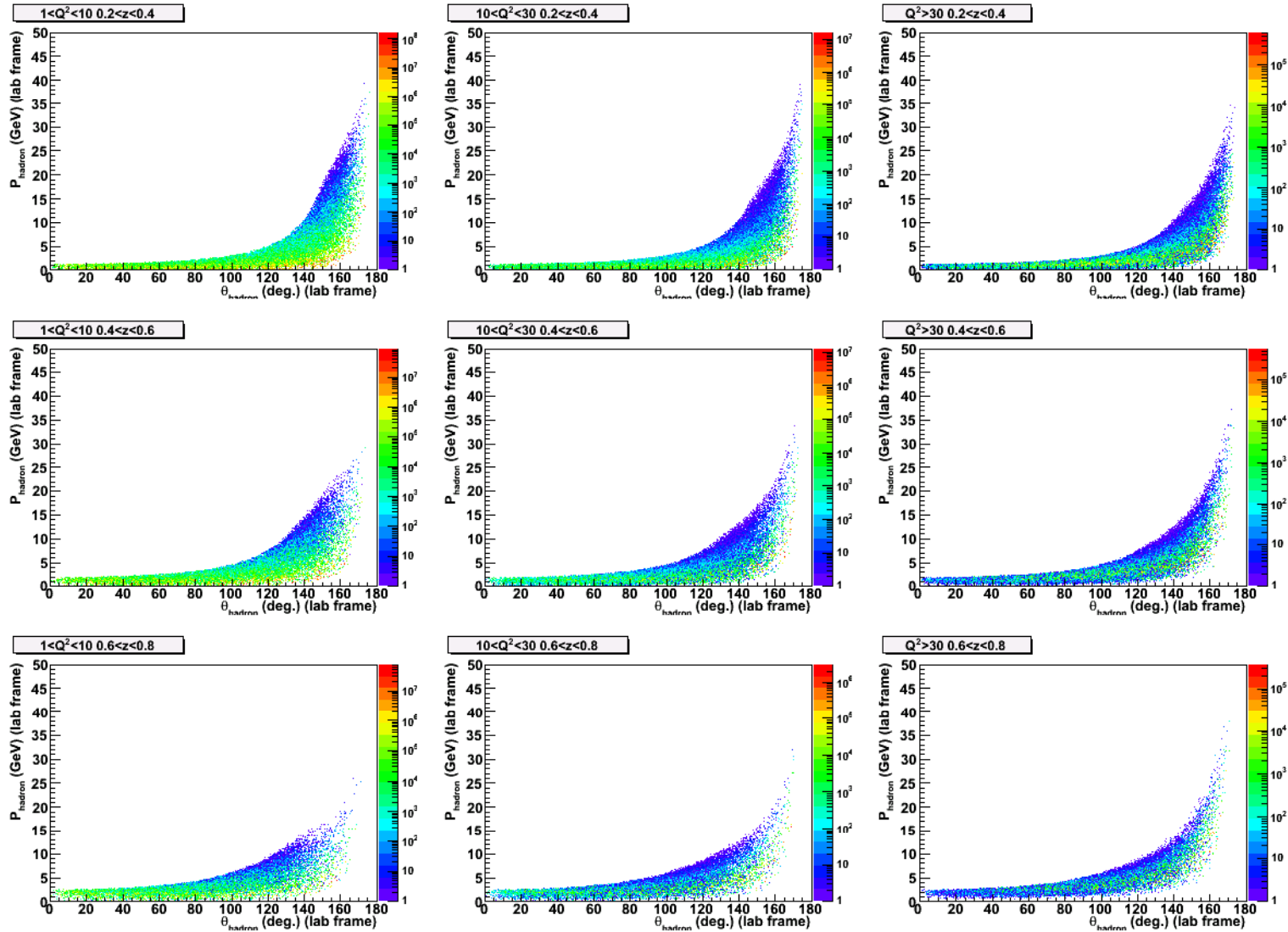# Backup

Quark spin and OAM on the lattice

(disconnected diagrams not yet included)
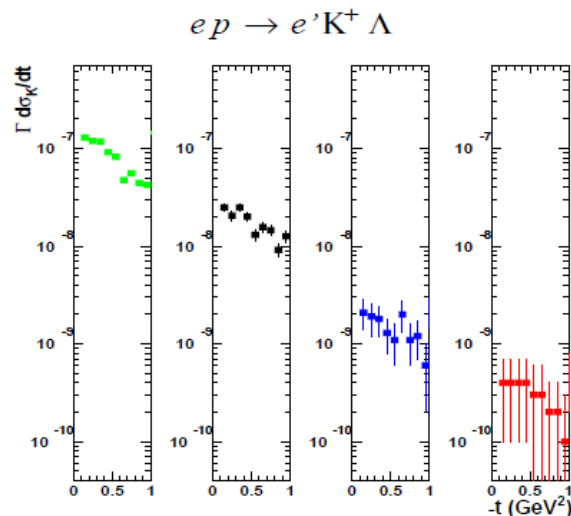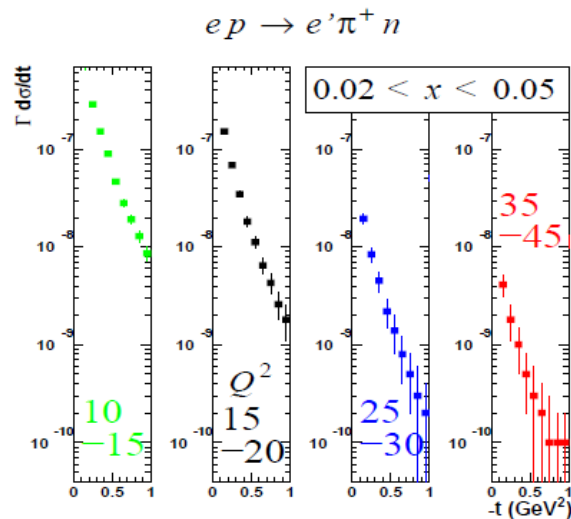

**L^u and L^d are significant but cancel**

SIDIS, leading mesons

- Lab momenta do not strongly depend on z and Q^2 (coverage ok even with cut on p).
- Meson momenta at extreme angles depend on the respective beam energies
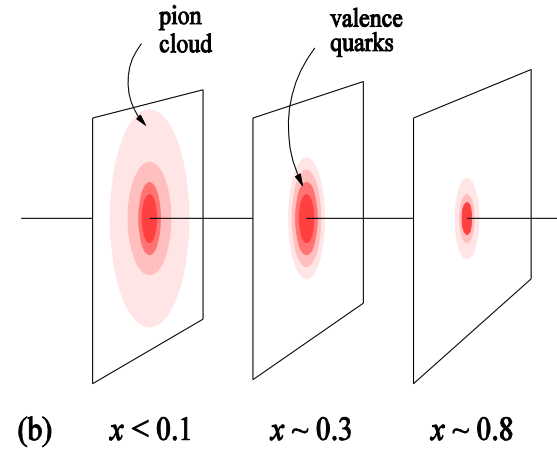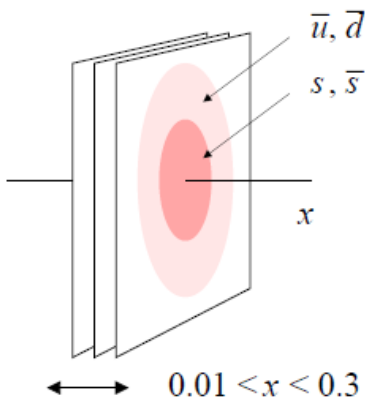
Transverse (sea) quark imaging

$ep \to e'\pi^+ n$

$0.02 < x < 0.05$

$ep \to e'K^+\Lambda$

- GPDs as "x-dependent form factors"
  - Fourier transform of t-distribution provides transverse image

pion cloud   valence quarks

(a)   (b) $x < 0.1$ $x \sim 0.3$ $x \sim 0.8$
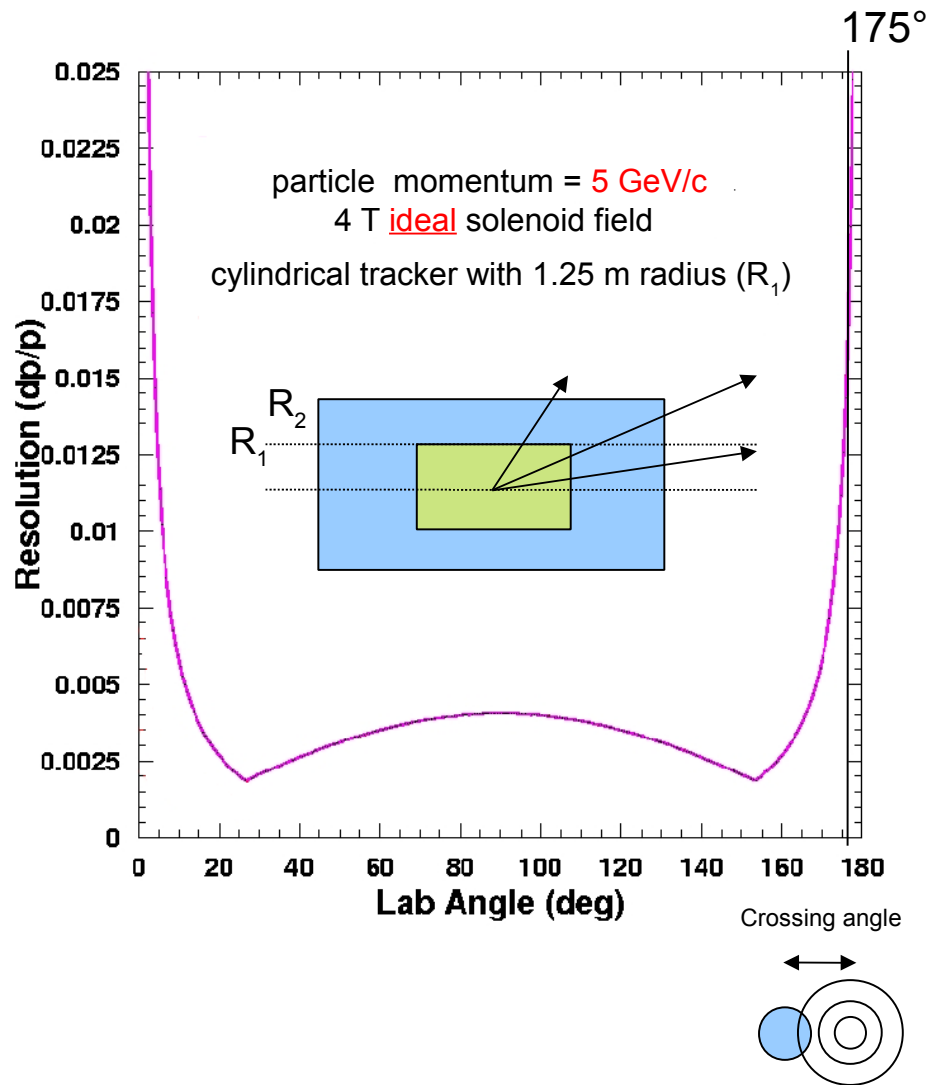
$\bar{u}, \bar{d}$

$s, \bar{s}$

$0.01 < x < 0.3$
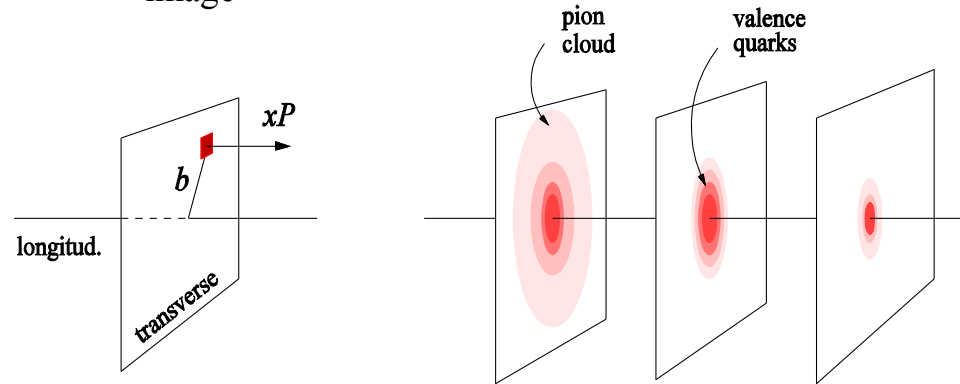
- Do strange and non-strange sea quark distributions have the same radius?
- πN or $K\Lambda$ components in nucleon?

T. Horn, C. Weiss

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Tracking momentum resolution in a solenoid field

175°

particle momentum = 5 GeV/c
4 T ideal solenoid field
cylindrical tracker with 1.25 m radius (R_1)

$$\Delta p/p \sim \sigma p / BR^2$$

- Tracker (not magnet!) radius R is important at central rapidities

- Only solenoid field B matters at very forward rapidities

Radial space is at a premium if one wants to reach a good momentum resolution over a wide angular range

Crossing angle

- A 2 Tm dipole covering 3-5° can eliminate divergence at small angles

- A beam crossing angle moves the region of poor resolution away from the ion beam center line.
  - 2D problem!

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Barrel RICH ideas for ALICE
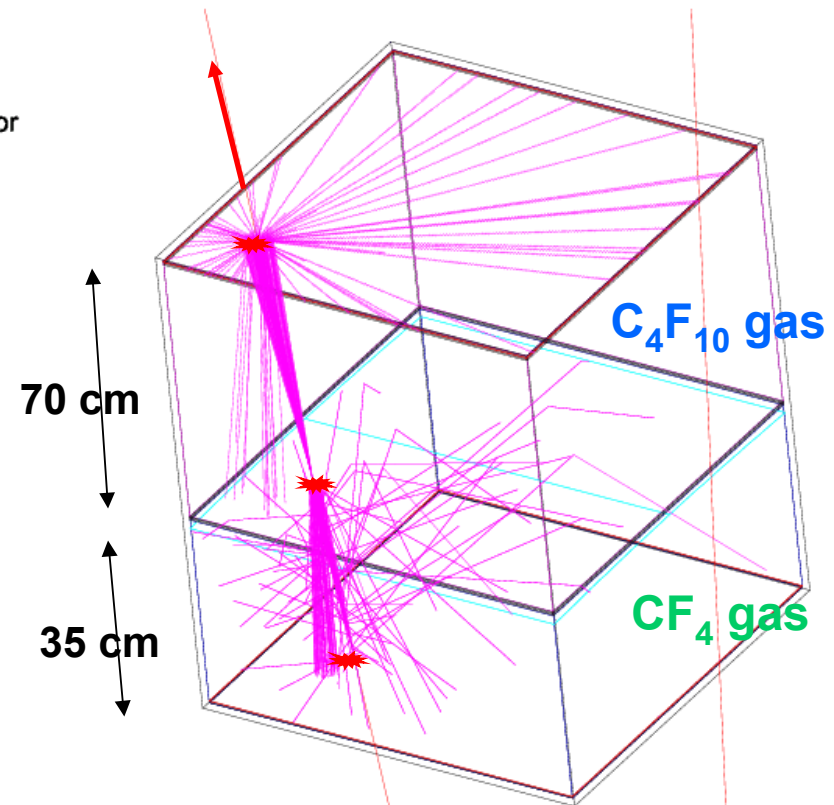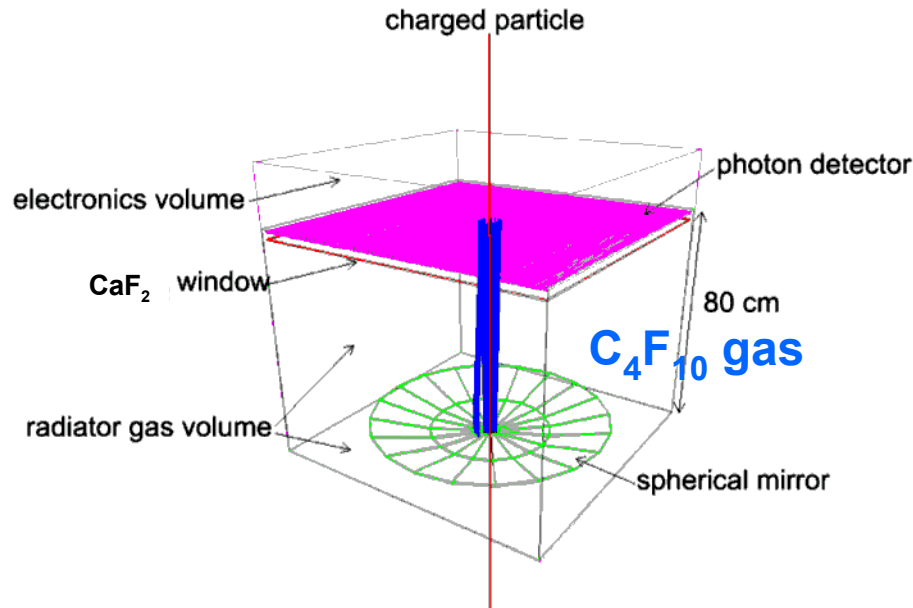
- ALICE barrel RICH with C_4F_{10} gas would extend the maximum momentum coverage from 9 to 14 GeV compared with a threshold Cherenkov, but requires 80 cm for radiator alone.

- Adding a second radiator with CF_4 gas (n = 1.0005) would increase radiator length to 105 cm

- Kaon momenta up to 4+ GeV/c would still need to be covered by aerogel or a DIRC

- ALICE ideas suggest that it may be possible to cover a wide range of momenta in the central detector, but it would require a detector with a very large radius (and hence weak solenoid field)

DIRC CHALLENGES: PHOTODETECTORS

PANDA DIRCs are asking a lot of fast compact multi-pixel photon detectors

- Single photon sensitivity, low dark count rate;

- Reasonably high photo detection efficiency;

- Fast timing: σTTS $\approx$ 50-100 ps (Barrel: 100-200 ps);

- Few mm position resolution;

- Operation in up to 1.5 T (Barrel: ~1 T) magnetic field;

- Tolerate high rates up to 2 MHz/cm2 (Barrel: 0.2 MHz/cm2);

- Long lifetime: 4-10 C/cm2 per year at 106 gain (Barrel: 0.5 C/cm2/yr).
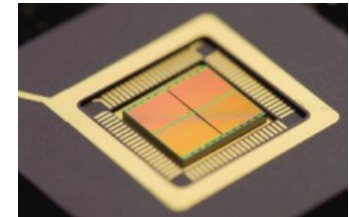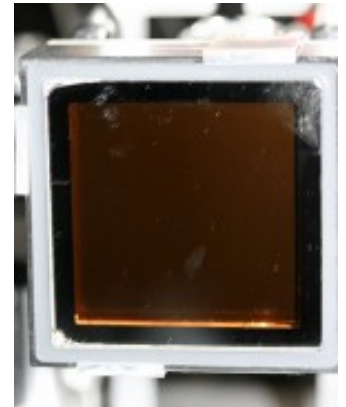
No currently available sensor matches all criteria;
   promising candidates: MCP-PMTs, MAPMTs, SiPM.

Digital SiPM (Philips) promising sensor for Disk: excellent timing and lifetime, integrated
    readout electronics, masking of hot pixels.
    But: needs cooling, needs redesign for single photons, new technology, prototypes only.

PANDA: BARREL DIRC READOUT ELECTRONICS

Electronics design demanding

- Signal rise time typically few hundred picoseconds.

- 10-100x preamplifier usually needed.

- High bandwidth 500MHz – few GHz (optimum bandwidth not obvious).

- Pulse height information required for < 100 ps timing (time walk correction),
    and desirable for 100-200 ps timing (ADC / time over threshold / waveform sampling / ...)

- PANDA will run trigger-less.

- Large data volume (Disk: up to 200 Gb/s).

- Example:
    HADES TRB board with NINO TOF add-on in
    GSI test beam in 2009, updated TOF add-on in
    test beams at GSI (next week) and at CERN in July.

- Significant development effort ahead.

- dSiPM with digitization on chip – no TDC, preamp,
   ADC, etc development required.

HADES TRB w/ NINO
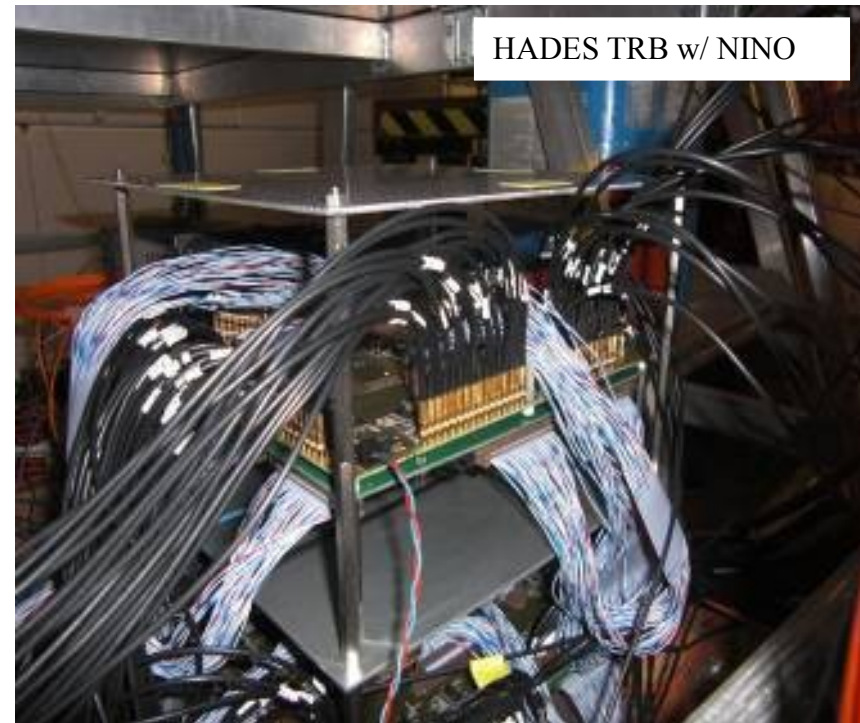
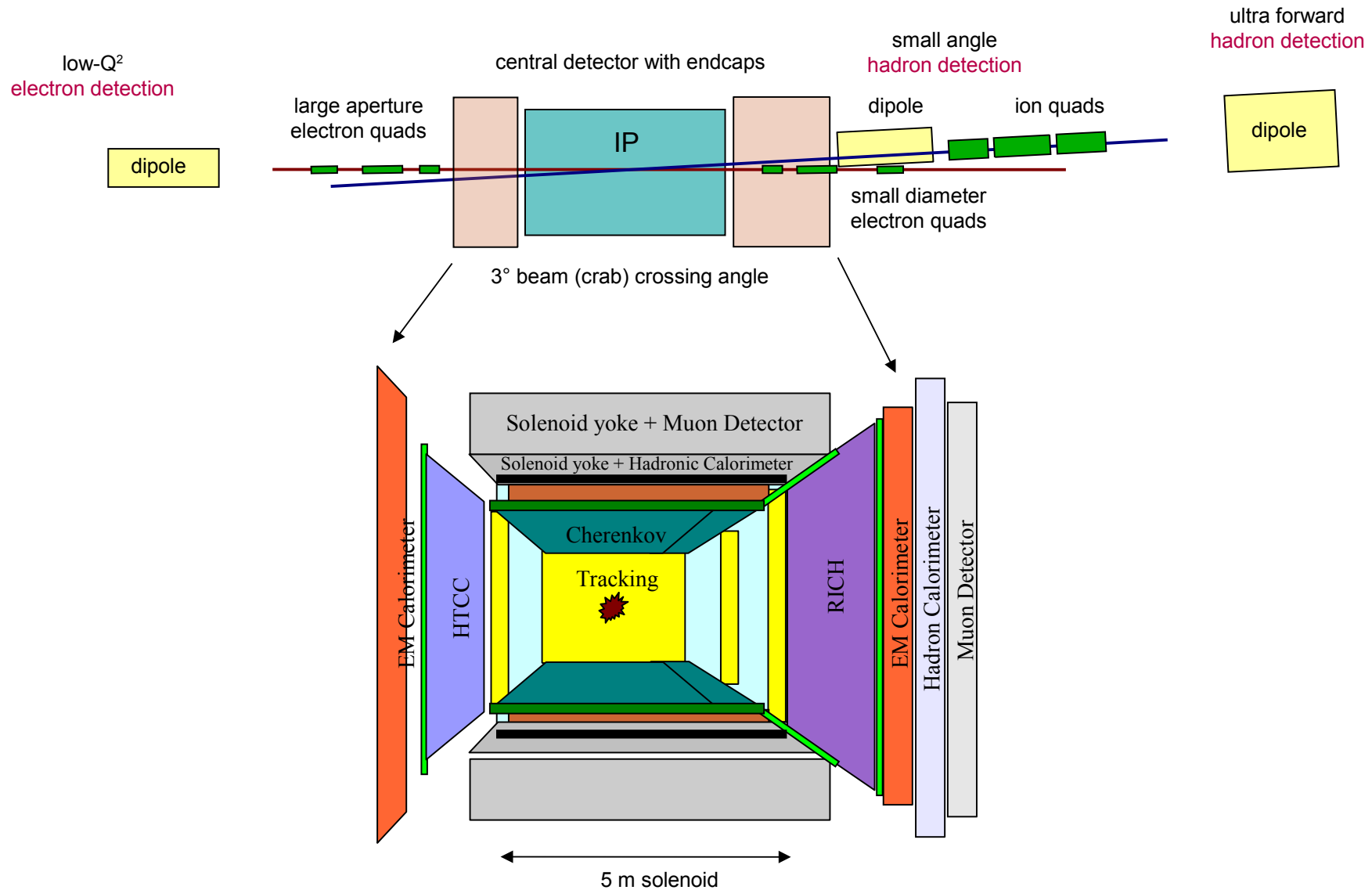# DIRC "camera" (expansion volume + sensors)

BaBar

PANDA

DIRC

DIRC
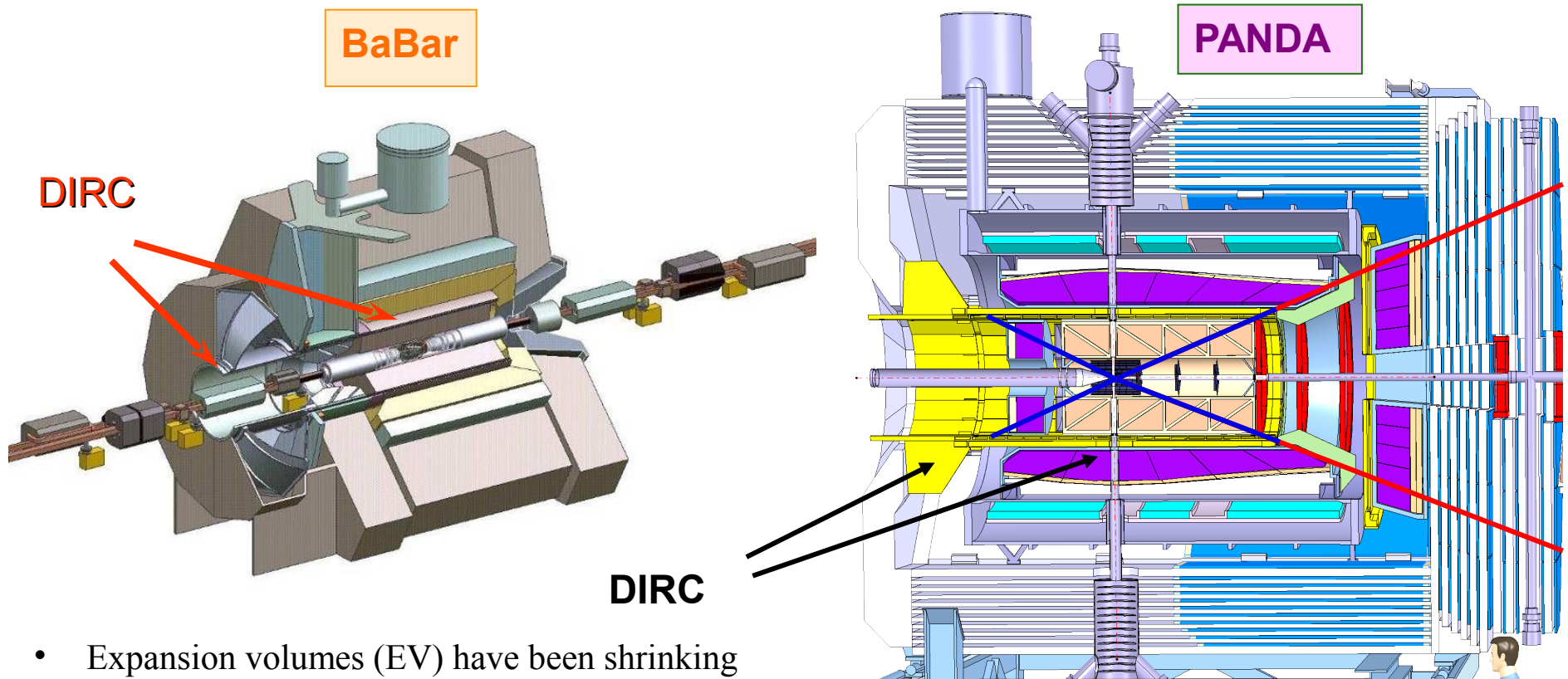
- Expansion volumes (EV) have been shrinking
  - BaBar: 1.2 m long tank with 6000 liters of water
  - PANDA: 30 cm long, 30 cm high EV with mineral oil
  - SuperB: 22 cm long, 56 cm high EV of fused silica

- Due to space constraints, the Belle II Time Of Propagation (TOP) DIRC sacrifices spatial resolution (originally also only in one dimension) for compactness of the expansion volume (10×10 cm^2).
  - Difficult to push performance using time only, in particular for long DIRC bars

DIRC inside of gas Cherenkov
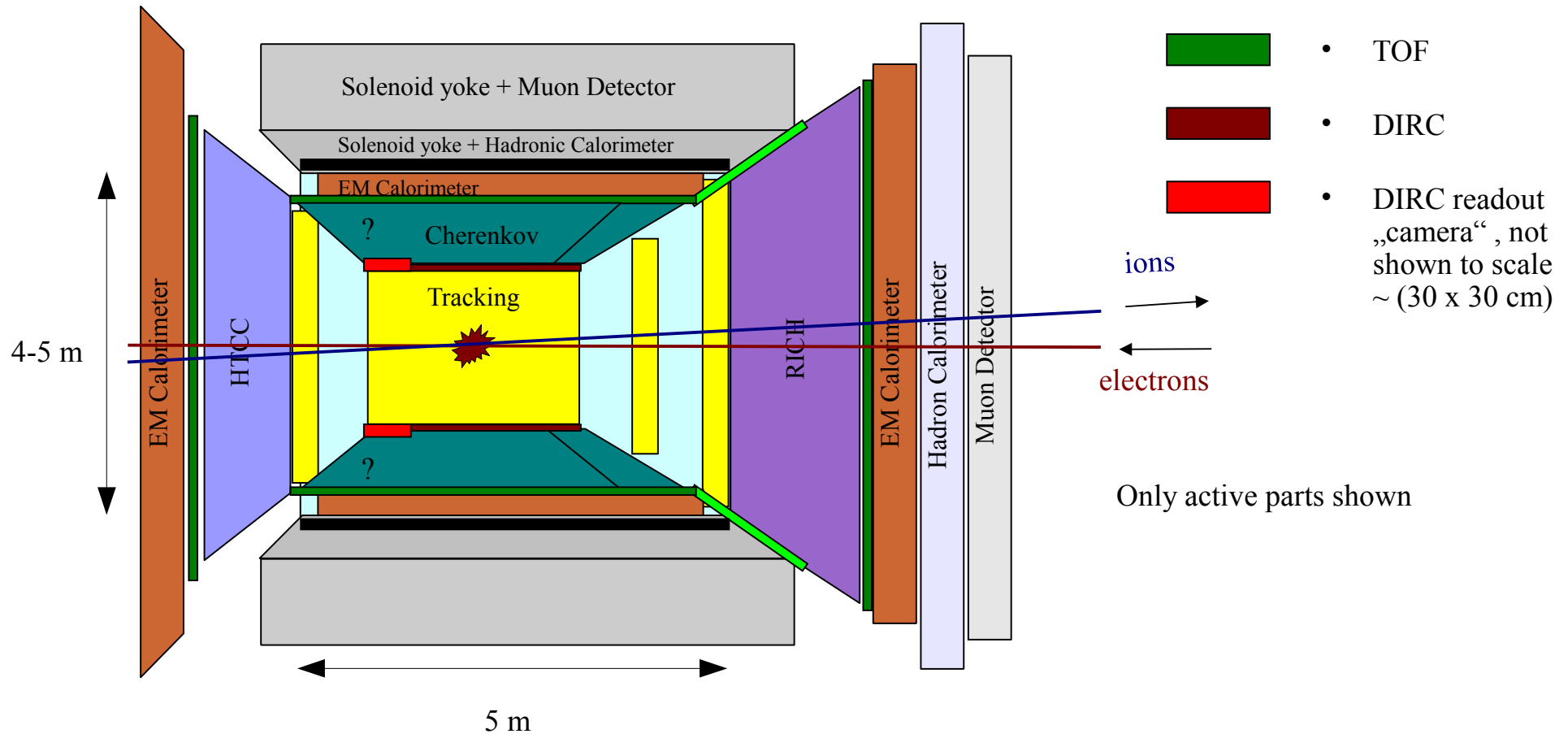
- *Pros:* lower DIRC cost and better timing
- *Cons:* more mass in front of Cherenkov, larger distance to TOF
- Part shadowed by DIRC readout can be optimized

Interaction Region – overview

Forward detection in GEANT4